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Developmental Patterns of Cognitive Abilities

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Abstract

The present study was designed to investigate: 1. age-related changes in cognitive performance and 2. the emergence of sex differences in cognitive performance. Two hundred and fifty children aged 9 to 12 years completed a battery of six cognitive tasks including two sets of abilities: the verbal cognitive battery included verbal fluency and short-term memory tasks; the visuospatial battery included mental rotation, localization, and form completion tasks. Results showed age-related improvement in all cognitive tasks except in serial sounds, with apparent variability in the magnitude of improvement across tasks. Furthermore, girls outperform boys in verbal fluency and in serial digits across age groups; no significant differences were found in visuospatial abilities. Findings are discussed for the biological as well as environmental sources for the developmental patterns of age-related improvement in cognitive performance as well as with regard to the emergence of sex differences in cognitive performance, and the potential role of intervention programs bridging the sex gap in visuospatial abilities.

Keywords: Cognitive abilities; Sex differences; Developmental pattern

Introduction

Developmental studies of cognitive abilities from infancy to adulthood show improvement in a wide range of domains. Nevertheless, high variability in the rate of improvement was documented, suggesting cognitive systems differ in their maturation rate [1]. Gur et al. [2] found age-related effects on performance across all cognitive domains that have been examined; however, some domains demonstrated larger age differences than others. For example, the largest age difference in performance was found for two executive domains: working memory and attention, which had received support from earlier publications [3], whereas, for mental flexibility and abstraction small to moderate effect sizes for improvement with age were found. Other findings regarding visuospatial performance have also documented improvement with age. For example, Merrill et al. [4] explored 6- to 12-year-old boys' and girls' route learning performance and found moderate effect size. These age-related changes in cognitive performance have been associated with age-related changes in neural substrates [5-7]. Studies using structural and functional neuroimaging paradigms have identified a central role for frontal and parietal regions in cognitive development patterns [8].

Alongside age influences on cognitive performance, individual differences and especially sex differences have been extensively studied. Sex differences in cognitive abilities received consistent support in adults. Men outperform women in visuospatial abilities, whereas women outperform men in verbal abilities [9,10]. Research on visuospatial abilities found that men outperform women on many tasks (e.g., navigation strategies and geographic orientation; [11-13], with the largest effect size found for mental rotation [14-19]. Women have been found to outperform men in verbal abilities, especially verbal memory [20,21] and verbal fluency [15,22] In other domains, such as vocabulary, verbal reasoning, and line orientation [23], the findings are inconsistent.

In comparison with the consistency found in adults for sex differences in cognitive abilities, empirical evidence for sex differences in cognitive abilities prior to puberty did not produce unequivocal findings. For example, in contrast to the clear evidence for the male superiority in mental rotation tasks among adults, findings of pre-puberty children are inconsistent. While some studies have demonstrated that the male advantage in mental rotation is apparent as early as infancy [24,25], other studies did not document sex differences in mental rotation in this early developmental stage [26,27]. In a similar vein, a line of studies exploring the developmental pattern of sex differences in mental rotation performance in children also provide mixed results. Frick et al. [28] found sex differences in mental rotation task involving matching between puzzle pieces and their placement hole at age 5 but not at age 4. Neuburger et al. [29] documented sex differences in mental rotation tasks in the fourth but not in the second grade. In contrast, Hawes et al. [30] did not document sex differences in children aged 4-8 years, with either 2-D or 3-D tasks. Palejwala and Goldenring [31] aimed to capture a wide developmental span, ages 2 to 7 years, in order to examine sex differences across these ages. They examined, among others, sex differences in visual processing via block design and object assembly tasks, and found that sex differences at ages 2 to 3 were absent, whereas they emerged at ages 4 to 7.

Studies exploring sex differences and developmental aspects in verbal abilities have suggested they seem to appear early in life. For example, Lutchmaya et al. [32] demonstrated that girls show superiority to boys in vocabulary development, with 2-year-old girls using significantly more words than boys. The developmental patterns of sex differences were also examined in a meta-analysis conducted by Hyde and Linn [33] in various verbal abilities (e.g., vocabulary, comprehension) in different age groups. They found that across verbal tasks sex differences were shown in children younger than 5 and in adults over the age of 26. In between, there were no notable sex differences.

Sex differences in short-term memory in children usually do not generate significant results. For example, no sex differences were found in verbal and spatial spans tasks in children aged 5 to 13 [34].

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Other studies using diverse measures such as picture memory task and location memory task in children aged 2 to 7 [31] or listening recall, digit recall, and word recall tasks in children aged 4.5 to 12 [35] did not produce significant results. In contrast, Keith et al. [36] reported sex differences in short-term memory with the use of a latent variable approach. Girls outperformed boys at ages 5 to 13, whereas boys outperformed girls at ages 14 to 17.

The apparent developmental pattern of sex differences in cognitive abilities showing consistent findings among adults while inconsistency among children, supports the held view that sex differences in cognition become more common or magnified during adolescence [37]. The underlying mechanism for this pattern involves a complex interplay between biological and environmental variables. Among the biological variables, sex hormones, including androgens, estrogens, and progestins, have been suggested as important factors [9]. Their greatest effect occurs during sensitive periods in development (prenatal or neonatal and postnatal [9,38]. It has been suggested that these sensitive periods in hormonal secretion are associated with sex differences in cognitive abilities [23,39,40]. Puberty has been indicated as a sensitive period of sex hormone-dependent brain organization, with increased levels of sex hormones secretion influencing changes in cognitive performance [41,42]. Studies on brain development in adolescence showed that trajectories of white and gray matter development during adolescence are sexually dimorphic [43]. Furthermore, sexual dimorphism appears in brain regions containing significant populations of sex hormones [44], which in turn, are involved in individual differences in functions such as cognitive abilities [37].

The present study aimed at investigating the developmental patterns of cognitive abilities prior to puberty in several cognitive domains (including verbal, memory, and visuospatial abilities), in order to shed light on age-related changes in cognitive performance, adding to the existing literature with a specific age range (9 to 12, prior to puberty), and a variety of cognitive tasks. Therefore the first hypothesis of the present study is: age-related changes in each cognitive domain are apparent with improvement in performance as a function of age. However, variability in improvement rate is found. Furthermore, the present study explored sex differences in cognitive abilities in children aged 9 to 12 years in order to reveal when these differences appear in each cognitive domain. Although previous studies addressed this issue in various age groups, cognitive tasks, and paradigms, the present study includes a valid battery familiar to the present age range, providing an opportunity to track the emergence of sex differences in each cognitive ability prior to puberty, which has been proposed as a sensitive period of establishing sex differences in cognitive abilities. Furthermore, the present study focused on tasks that yielded pronounced sex differences in former studies (e.g., mental rotation, verbal fluency). Therefore, it is hypothesized that: girls outperform boys on verbal abilities across age groups, whereas no significant sex differences are found on visuospatial and memory abilities.

Methods

Participants

Two hundred and fifty elementary-school children participated in the present study. Sixty of the participants were third graders (mean age 8.96 ± 0.25), 65 were fourth graders (mean age 10.03 ± 0.27), 66 were fifth graders (mean age 11.06 ± 0.26), and 59 were sixth graders (mean age 11.97 ± 0.24). Participants were from 4 schools in Israel. The schools were selected so as to be homogeneous with respect to socioeconomic background of the children (2 schools from medium-high socio-economic status and 2 schools from low socio-economic status communities). One hundred and twenty-six of the participants were female and one hundred and twenty-four were male. All participants were right-handed according to their subjective reports. All were native Hebrew speakers with no known diagnosis of serious medical or psychiatric illness. Children were recruited as part of their school assignment, following their parents providing their consent for their child's participation.

Measures

The study included demographic questions (sex, age) and six cognitive tests that participants performed on a computer and using paper and pencil.

Cognitive test battery

Six types of tasks were presented to the participants: three verbal and three visuospatial cognitive [45].

Verbal cognitive tasks

Serial sounds: Eight easily recognizable sounds (e.g., telephone ringing, chicken clucking) were presented in sequences of 2, 3, 4, 5, 6, 7, and 8 items. Immediately after each sequence, participants were instructed to list the sounds in the same order.

Serial digits: Digits (between 0 and 9) were presented in sequences of 2, 3, 4, 5, 6, 7, 8, and 9 digits. Immediately after each sequence of numbers, participants were instructed to list the digits in the same order.

Verbal fluency: Participants were asked to generate as many words as possible beginning with three specified letters of the Hebrew alphabet (A, B, D). Proper names and different forms of the same word (e.g., plurals) were not allowed. One minute was allocated for each letter. The score represented the number of words generated for all three letters.

Visuospatial cognitive tasks

Mental rotation task: A computerized task involved three models (2-D abstract stimulus) that were presented randomly on the screen. Pairs of photographs of each model were prepared, in which the models appeared to be nearly identical, except that they were rotated in space with respect to each other. Participants were presented three models at a time and were instructed to decide which two models were the same by mentally rotating them. Each trial was displayed for 30 seconds and was separated from the next pair by a rest period of 5 seconds, during which a white screen was displayed. Eighteen trials were used; on each trial a score of 1 or 0 was given, and then summed for each participant.

Localization: An "x" was shown at a certain location on a blank rectangle for 3 seconds. Participants were instructed to place the mouse arrow in the same location on a parallel blank rectangle with maximum accuracy. Absolute distance was calculated with a higher score representing a poorer performance. Eighteen trials were presented, each lasting 20 seconds.

Form completion (closure speed): Twelve incomplete silhouettes of familiar objects or scenes were presented in the form of black-and-white paper cutouts on the computer screen. The items were chosen to be as culture-free as possible. Participants were instructed to imagine the complete silhouette and to identify and describe the object in one or two words. Participants were given 20 seconds for each silhouette; on each trial a score of 1 or 0 was given [46].

Procedure

The study was approved by the institutional review board. Participants completed a brief demographic questionnaire followed by the cognitive tests. For the computerized tasks, participants were asked to position their heads approximately 50 cm from the center of the monitor and to focus their gaze on the center of the screen. The cognitive tests took approximately 60 minutes.

Statistical analysis

Cognitive ability variables were standardized to z-scores based on the means and SDs of the entire sample. Higher z-score reflects better performance (localization z-score was multiplied by −1 in order to generate the score in the same direction as the other measures). First, a series of t-tests was conducted to rule out interference with socio-economic status (based on participant's school). Six t-tests were analyzed with participant's school as the independent variable and the cognitive task as the dependent variable. All analyses yielded non-significant results (p>.05). Therefore this variable was excluded from further analyses. Next, mean scores for performance across the sample on each task were calculated alongside correlations with age. Next, two separate two-way MANOVAs for the visuospatial tests and for the verbal tests were performed with sex and age as independent variables. The significant multivariate tests were followed by univariate F tests, and those yielding significant findings for the age of participants were followed by post hoc tests using Scheffe's Test in order to identify significant differences in the means scores between age groups. Effect sizes were calculated for significant main effects using partial eta-squared (η^2_p) for age, and for sex.

Results

Full sample performance

Table 1 shows mean and SD on each task across samples, and includes the correlations between age and performance on each cognitive task for the full sample. All correlations were positive and significant (except the correlation with serial sounds, which was marginally significant), reflecting improvement in performance with age. Correlations varied in their magnitude with the highest correlation between age and serial digits, followed by form completion, and the lowest for serial sounds (*ns*) and mental rotation.

Age, sex, and verbal abilities

Two-way MANOVA was conducted with sex (male, female) and age group (9, 10, 11, 12) as independent variables on the verbal tasks: serial sounds, serial digits, and verbal fluency. A significant multivariate effect for age on the three dependent variables was found (Wilk's lambda=0.57, F (9, 576)=16.90, p<0.001; η^2_p=0.17). Each dependent variable was subjected to a further ANOVA in order to examine whether the trend is the same for each of the verbal tasks. For verbal fluency and for serial digits the differences between age groups were significant [F (3, 239)=14.18, p<0.001; η^2_p=0.15 for verbal fluency; and F (1, 239)=55.71, p<0.001; η^2_p=0.41 for serial digits). Post hoc analysis using Scheffe's Test showed that performance on verbal fluency and serial digits was higher for ages 11 and 12 (with no significant difference between them), followed by a lower performance at age 10, and last at age 9 on both tasks. However, differences in serial sound task were not statistically significant (F (1, 239)=1.71, p>0.05; η^2_p=0.02). A significant multivariate effect for sex on the three dependent variables was found (Wilk's lambda=0.88, F (3, 237)=11.10, p<0.001; η^2_p=0.12; (Figure 1). Each dependent variable was subjected to a further ANOVA in order to examine whether the trend is the same for each of the verbal tasks. For verbal fluency and for serial sounds the difference between boys and girls was significant (F (1, 237)=29.62, p<0.001; η^2_p=.011 for verbal fluency; and F (1, 237)=6.53, p<0.05; η^2_p=0.03 for serial sounds), with girls outperforming boys. However, differences in serial digits tasks were not statistically significant (F (1, 237)=0.75, p>0.05; η^2_p=0.00). The interaction between sex and age group was not statistically significant (Wilk's lambda=0.97, F (3, 576)=0.94, p>0.05; η^2_p=0.01).

Variables	M	SD	r	p
Serial sounds	83.82	41.87	0.62	0.062
Serial digits	12.92	6.99	0.62	0.000
Verbal fluency	20.09	8.04	0.36	0.000
Mental rotation	14.41	5.47	0.19	0.004
Localization	1.84	.61	0.48	0.000
Form completion	12.25	7.45	0.54	0.000
Note. The localization score is higher for poorer performance.				

Table 1: Means (raw scores), SD, and correlations with age.

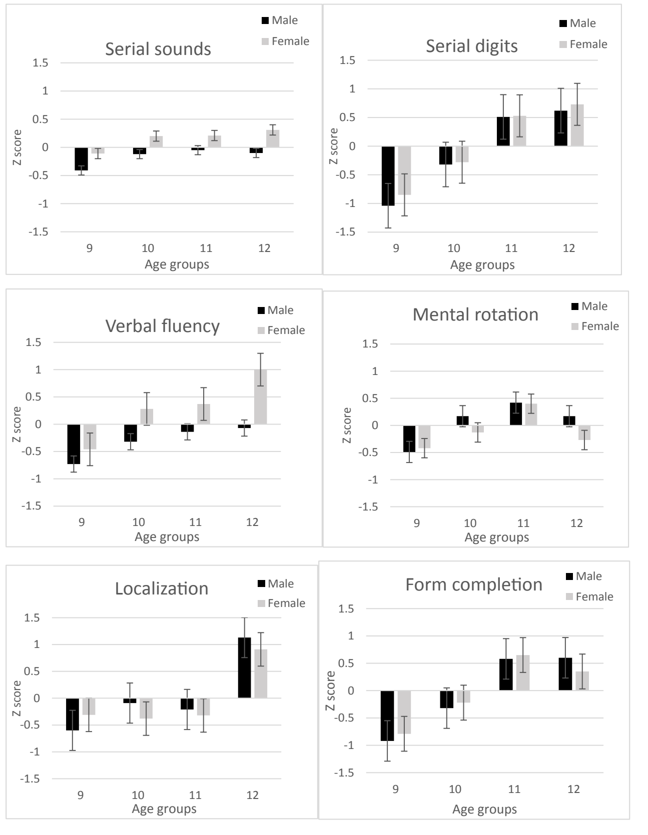

Figure 1: Means (± SE) of Z-scores for verbal cognitive tasks: serial sounds, serial digits, and verbal fluency; for visuospatial cognitive tasks: mental rotation, localization, and form completion. The results are shown by age groups (9 to 12).

Visuospatial abilities

Two-way MANOVA was conducted with sex (male, female) and age group (9, 10, 11, 12) as independent variables on the visuospatial tasks: mental rotation, localization, and form completion. A significant multivariate effect for age on the three dependent variables was found (Wilk's lambda=0.42, F (9, 552)=26.27, p<0.001; η^2_p=0.25). Each dependent variable was subjected to a further ANOVA in order to examine whether the trend is the same for each of the visuospatial tasks. For mental rotation the differences between age groups was significant (F (1, 237)=8.92, p<0.001; η^2_p=0.11). Post hoc analysis using Scheffe's Test showed that performance on mental rotation was higher for age 11, followed by a lower performance at age 10, and last at ages 9 and 12 (with no significant differences between these groups). For form completion the differences between age groups was significant (F (3, 237)=45.25, p<0.001; η^2_p=0.37). Post hoc analysis using Scheffe's Test showed that performance on mental rotation was higher for ages 11 and 12 (with no significant difference between them), followed by a lower performance at age 10, and last at age 9. For localization the differences between age groups was also significant (F (3, 237)=38.00, p<0.001; η^2_p=0.33). Post hoc analysis using Scheffe's Test showed that performance on localization was higher for age 12 compared with ages 9-11 (no significant differences between these age groups). There was no multivariate effect for sex for the three dependent variables (Wilk's lambda=0.99, F (3, 227)=0.85, p>0.05; η^2_p=0.01). The interaction between sex and age group was not statistically significant either (Wilk's lambda=0.97, F (9, 552)=0.89, p>0.05; η^2_p=0.01).

Discussion

The present study investigated the influence of age and sex on cognitive performance. As expected, across all cognitive domains (except for serial sounds, which yielded only marginally significant correlation) cognitive performance improved with age. However, there was substantial variability in the rate of improvement. Large effect sizes were obtained for serial digits, form completion, and localization, followed by verbal fluency and mental rotation. The largest effect size obtained for serial digits confirms previous findings for substantial improvement in working memory with age [2]. Based on evidence associating age-related changes in specific cognitive tasks and changes in the neural substrates in the prefrontal lobe in childhood and adolescence, working memory together with other executive functions has been documented as influenced by maturation [3,8]. The additional two large effect sizes found for form completion and localization – two visuospatial tasks, are in accord with previous suggestions for age-related maturation for executive functions [47]. Visuospatial abilities place demands on executive functioning, and in particular the spatial visualization and spatial relations factors needed for performing visuospatial tasks. In the present study, form completion and localization tasks share these particular aspects of spatial visualization and spatial relations, and therefore demand executive functioning. Luciana et al. [48] employed a localization task similar to the one used in the present study together with other spatial tasks in order to investigate developmental patterns in spatial abilities from childhood into adolescence. They found that executive aspects of spatial working memory develop into adolescence and proposed an association with prefrontal organization as a function of maturation that promotes successful task performance. The present finding failed to show age-related improvement in serial sound task. This is line with previous findings for age-related improvement in memory performance. Gur et al. [2] suggested that perhaps the steep development gains for memory are taking place earlier in development, supported by evidence for early maturation of temporal lobe structures [49].

Sex differences were found for verbal abilities across age groups, whereas on visuospatial abilities no sex differences were found. Girls outperformed boys in verbal fluency and in serial sounds abilities, with no statistical indication of these differences magnified throughout development. This finding is in line with previous studies demonstrating the emergence of sex differences in verbal abilities in childhood. For example, in a cross-sectional study of children aged 12-14, Herlitz et al. [37] showed sex differences in verbal fluency without any indication for a larger magnitude during adolescence. Supported by evidence related to sex differences in cortical development [50], their findings joined with the present findings indicate that sex differences in verbal abilities emerge before puberty and imply that the source of these differences should be sought early in development. The present study also found sex differences favoring girls in serial sounds across age groups. The serial sound task is presumed to depend upon both verbal and nonverbal processing [51]. Performance on this task requires short-term maintenance of verbal information in addition to further mental manipulation of the stored information [52]. Although previous studies investigating sex differences in memory among adults usually demonstrated female superiority in various memory tasks, such as short-term word-recognition-memory [22], verbal learning and short-term memory [20] and free recall [21], studies on sex differences in memory tasks in children usually implied no sex differences [31,35]. Inconsistency in findings may be related to the various paradigms used, including differences in sensory modalities and the nature of stimuli. Future studies should continue exploring the developmental patterns of sex differences in memory abilities using a wide range of tasks, in order to reveal the conditions under which the female superiority prevails alongside the underlying processing mechanisms involved in each examined ability and to pinpoint the time segment in development in which these differences emerge.

With regard to visuospatial tasks, numerous studies have shown that the largest effect size of sex differences was found for mental rotation task [53,54]. The present study aimed at capturing the emergence of sex differences in mental rotation and other visuospatial abilities, and found that on all three visuospatial tasks, including mental rotation, boys and girls did not differ in their performance. Previous studies investigating sex differences in mental rotation performance in children yielded inconsistent results. However, they differed substantially in the presented stimuli. Adult studies are traditionally based on [55] three-dimensional mental rotation task in which participants are required to mentally rotate an object in three dimensions to determine its matching to one of several other objects. Previous studies suggested that 3-D tasks may be too cognitively demanding for children. The present study used a 2-D abstract stimuli. Other studies tested children's performance on various 2-D stimuli using animal drawings or other familiar objects, alphanumeric stimuli, or abstract characters, and showed that various 2-D stimuli differ in their difficulty level. Performances for familiar 2-D stimuli (e.g., animal drawings or alphanumeric stimuli) were found to elicit higher accuracy scores and shorter response time as opposed to abstract characters [56-59].

The absence of sex differences in visuospatial abilities across age groups can be explained on the basis of biological as well as environmental perspectives. Among the biological variables, sex hormones have been proposed as playing a central role in sex differences in adulthood. Puberty has been suggested as a sensitive period of sex hormone-dependent brain organization, with increased levels of sex hormones secretion influencing changes in cognitive performance [41,42]. Support for this suggestion arises from studies on sex differences in brain structure and function. For example, sex differences in brain activation were demonstrated in adults in brain regions containing significant populations of sex hormones [44]. Among the environmental variables influencing the development of sex differences in visuospatial abilities, gender role representations have been suggested as a key variable. Gender roles develop in childhood through modeling and are later manifested in gendered beliefs and behavior [60]. Endorsement of external models representing beliefs concerning abilities, may lead to internal representations of the child's strengths and weaknesses, and in turn may lead to avoidance behaviors among girls who decrease their own spatial self-concept [29]. An integrative approach, including biological as well as environmental factors accounting for sex differences in mental rotation abilities has been proposed in a recent review [53]. The integrative attempt regarding gene×environment interaction influencing spatial performance suggests that the preliminary male advantage in these tasks led them to become more interested in these activities, which in turn led to a greater spatial advantage [61].

Taken together, the present findings showing the absence of sex differences prior to puberty highlight the need for intervention in education programs. Sex differences in spatial abilities have far-reaching consequences in girls' and women's representation in STEM (science, technology, engineering, and mathematics) fields [62]. Previous studies showed that training and engaging in spatial activities improves performance [63]. Therefore, early education and training at school should provide learning opportunities to exercise spatial skills [62] through toys and other tangible objects, through abstract problem solving, and other various play opportunities promoting spatial thinking.

Conclusion

To summarize, the present findings suggest age-related changes in cognitive performance in four age groups in childhood, showing variability in improvement rate. Future studies should further investigate these patterns and the neural substrates associated with them. Furthermore, the present findings showed that whereas girls outperform boys in verbal abilities, boys do not outperform girls in visuospatial abilities, contrary to the clear-cut advantage demonstrated in previous findings of men's superiority in these tasks. Four decades ago, Waber [64] postulated that sex differences in cognitive abilities could be explained by maturation rate. He suggested that through the mediation role of the development of hemispheric specialization, late maturers have better spatial abilities, whereas early maturers have better verbal abilities. The present findings provide partial support for this suggestion. Future studies should continue exploring the developmental patterns of sex differences, and their sources in biological (e.g., sex hormone measures) as well as environmental (intervention programs) variables.

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