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Childhood poverty: Specific associations with neurocognitive development

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ABSTRACT

Growing up in poverty is associated with reduced cognitive achievement as measured by standardized intelligence tests, but little is known about the underlying neurocognitive systems responsible for this effect. We administered a battery of tasks designed to tax-specific neurocognitive systems to healthy low and middle SES children screened for medical history and matched for age, gender and ethnicity. Higher SES was associated with better performance on the tasks, as expected, but the SES disparity was significantly nonuniform across neurocognitive systems. Pronounced differences were found in Left perisylvian/Language and Medial temporal/Memory systems, along with significant differences in Lateral/Prefrontal/Working memory and Anterior cingulate/Cognitive control and smaller, nonsignificant differences in Occipitotemporal/Pattern vision and Parietal/Spatial cognition.

1. Introduction

Beginning as early as preschool and persisting throughout childhood and beyond, individuals of low socioeconomic status (SES) perform below their middle class counterparts on tests of intelligence and school achievement (e.g., Bradley and Corwyn, 2002). Measured in standard deviation, SES gradients for cognitive achievement are even steeper than those for physical health (Duncan et al., 1998) and are likely to play a role in the persistence of poverty across generations.

Little is known about the underlying mental systems that mediate the SES disparities in cognitive performance. IQ tests and school achievement are valuable in that they have well-understood psychometric properties and predictive power concerning future life trajectory. However, they do not correspond in any straightforward way to the current scientific "parse" of cognitive function into underlying components. In the present investigation, we attempt to characterize the cognitive outcomes of childhood poverty in terms of the framework of cognitive neuroscience.

How and why might a sociological construct, SES, be associated with brain function? The answer lies in the nature of SES itself. Although SES is generally estimated by measuring parental education and occupational status, it encompasses far more than these simple indices, including associated differences in physical and mental health (Adler et al., 1994) and in physical and psychosocial aspects of the environment (Evans, 2004). Important psychosocial factors

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include the presence of both parents in the home and parental stress and depression. Physical factors include nutrition and exposure to pollutants. Any of these is, in principle, capable of influencing brain development and function. In addition, some of the variance in an individual's SES has been attributed to genetic factors (Lichenstein and Pederson, 1997), which could also be manifest in the brain.

Given the multiplicity of potential influences on brain development, it is possible that the SES gradient in cognitive achievement would have a broad and uniform neurocognitive basis, affecting all components of the developing mind and brain to a roughly equal degree. Alternatively, some components may be more sensitive to SES than others. In a preliminary study of low and middle SES kindergarteners (Noble et al., 2005), we found evidence of an uneven profile of differences between low and middle SES children. In that study, language and executive function were most strongly related to SES. The goals of the present study were to characterize the neurocognitive profile of SES in a new sample of older children, using a more fine-grained parse of neurocognitive systems, particularly prefrontal systems, as well as to rule out medical problems that could account for the SES disparities in cognitive performance.

Prefrontal/Executive function is of interest for several reasons. This brain region undergoes prolonged postnatal development (e.g., Casey et al., 2000; Fuster, 2002), as does its functional connectivity with other brain regions (e.g., Malkova et al., 2000), providing maximal opportunity for the different life experiences of lower and higher SES to influence the development of this region of the brain. Second, regions within prefrontal cortex have been associated with "general intelligence" of the kind tested by IQ tests (see Gray and Thompson, 2004, for a review), which is robustly associated with SES (Smith et al., 1997). Third, sociologists have attempted to generalize about socioeconomic status and cognitive style, with some suggesting that increasing SES is associated with increasing tendency to resist impulses and delay gratification (e.g., Banfield, 1968; Lewis, 1965), characteristics associated with prefrontal function (e.g., Miller et al., 2003). Fourth, earlier studies have found evidence that executive function differs as a function of SES in children. Mezzacappa (2004) assessed the sociodemographic correlates of performance on Posner's Attention Network Task (ANT; Rueda et al., 2004) and found the strongest relations with SES in what he terms "executive attentional" processes. The study of more general neurocognitive correlates of SES in kindergarteners, mentioned earlier, also found a large difference between the low and middle SES children in executive function (Noble et al., 2005).

What is unclear at present is which specific systems of prefrontal cortex might be involved with SES. The executive functions of prefrontal cortex are a complex assemblage of distinct (though highly interactive) neurocognitive systems. For example, the prefrontal subsystems associated with intelligence and with delay of gratification are different. The set of tasks used in the previous study of kindergarteners was heterogeneous, including working memory, cognitive control, set shifting, theory of mind and delay of gratification. In the present study, we attempt to discern with greater neurocognitive specificity the prefrontal correlates of SES, by separately assessing Lateral prefrontal/Working memory, Anterior cingulate/Cognitive control and Ventromedial prefrontal/Reward processing systems.

Our study of kindergarteners found that language ability, including vocabulary, syntactic ability and phonological awareness, is associated with SES, consistent with a body of literature on language development in poor and middle class children (Whitehurst, 1997). In more recent work, we have found that the relationship between phonological awareness and reading ability is modulated by children's SES (Noble et al., 2006), as is the relation between phonological awareness and brain activity in reading-related areas (Noble et al., in press). The present study focused on comprehension of single word lexical–semantics and sentence-level syntax.

Another system that will be examined anew in the present study is the memory system of the medial temporal lobes. This system underlies learning in the classroom as well as for virtually all real world activities, and its identity as a localized and dissociable neurocognitive system is well established on the basis of both functional neuroimaging and patient studies. Although the previous study of kindergarteners included tests of memory, they were in effect tests of immediate memory as each test was inadvertently administered immediately following exposure to the memory material. The present study addresses the relation between SES and the acquisition of more enduring memories.

In all, seven neurocognitive systems were assessed using pairs of dissimilar behavioral tasks, as described in greater detail in the Experimental procedures section. These comprised three Prefrontal/Executive systems, Lateral prefrontal cortex/Working memory, Anterior cingulate cortex/Cognitive control system and the Ventromedial prefrontal cortex/Reward processing system, and four other systems, the Occipitotemporal/Pattern vision system, Parietal/Spatial cognition system, Left perisylvian/Language system and Medial temporal/Memory system.

The final goal of this study was to assess the neurocognitive correlates of SES with minimal confounding by health factors. Given the higher prevalence of prenatal substance exposure, premature birth, illness and injury within low SES families (Adler et al., 1994), neurocognitive disparities could result from larger fractions of children with undiagnosed illness and injury being averaged together with healthy children at lower levels of SES. The low SES participants in the present study have been followed since birth by a pediatrician (HH) and have no known history of neuropsychiatric illness or neurologic insult. They give us a unique opportunity to study the neurocognitive profile of SES in healthy children.

2. Results

To reduce the effect of outliers, data from each task were Winsorized, that is, the two most extreme values at each end of the distribution of all 60 children's scores were replaced with the third most extreme value at each end. Performance in each task was then reviewed for ceiling and floor effects, defined as mean performance less than one standard deviation from the minimum or maximum possible. Performance on the Shape

Detection task was found to be at ceiling and was therefore excluded from further analysis.

In order to express performance in each task on a common scale for purposes of analysis, the data were transformed to z scores defined relative to the distribution of all sixty children. Composite scores for each neurocognitive system were then created by averaging the z scores for the two tasks of each system (one task for the Occipitotemporal/Pattern vision system). Multivariate analysis of covariance (MANCOVA) with factors SES, age and gender was then carried out on the 7 composite measures.[1]

The first question addressed by this analysis was whether there was a reliable SES disparity in performance of the task battery overall. This was confirmed by a significant effect of SES, $F(7,49)=3.63$, $p=.003$. This finding is consistent with the large literature already reviewed showing better performance on a wide range of cognitive tests with higher SES.

The next question was whether children's age or gender had a significant effect on their performance or modulated the effect of SES on their performance. No such effects were found. Neither age ($F(7,49)=1.17$, $p=.335$) nor gender ($F(7,49)=.55$, $p=.791$) influenced performance nor did these factors interact with SES (SES by age $F(7,47)=.96$, $p=.471$; SES by gender $F(7,47)=.97$, $p=.464$); or with each other (age by gender $F(7,47)=.66$, $p=.704$.

We then asked whether the effects of SES were uneven across different neurocognitive systems, in other words whether they were greater for some systems than for others, and whether this unevenness was more than would be expected by chance. Because all measures were z scores, we were able to answer this question by testing the interaction of SES with neurocognitive system in a mixed effects model with random coefficients for each composite score. This interaction was significant ($F(6,339)=3.00$, $p=.007$) indicating that the SES disparity in cognitive development is not uniform across different neurocognitive systems but rather is more pronounced for some neurocognitive systems than for others. The nonuniformity of SES effects is represented visually in Fig. 1, which shows the effect size for SES on each of the neurocognitive systems assessed.

The pattern of SES disparities across the different systems was then assessed using structural equation modeling. Model fit indicated that the effect of SES on language and memory was statistically different from the effect on other systems, which were not different from each other (Chi-square=5.95, $df=2$, $p=.051$).

SES disparities in specific neurocognitive systems were then examined individually using t tests ($df=58$). We begin with those systems for which there were a priori predictions of SES disparities: the three Prefrontal/Executive systems and the Left perisylvian/Language system. On the basis of previous research showing SES disparities in language ability, we expected to find a significant difference in this system and did, $t=4.96$, $p<.001$. We also found a significant SES disparity in the Lateral prefrontal/Working memory composite, $t=2.55$, $p=.013$, as well as a borderline significant trend toward the predicted SES difference in the Anterior cingulate/Cognitive control composite, $t=1.91$, $p=.062$. In contrast, the effect of SES on the Ventromedial prefrontal/Reward processing composite was not significant, $t=.43$, $p=.668$.

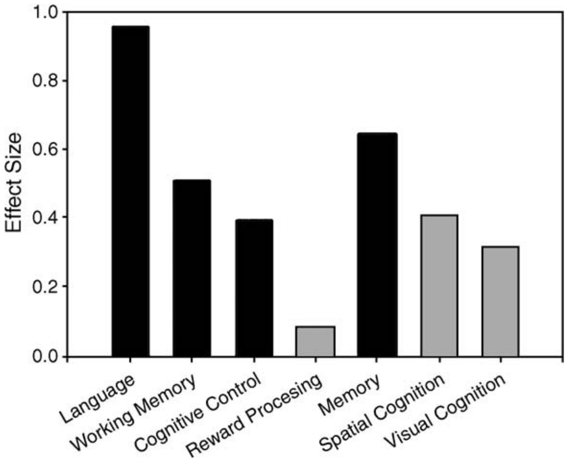

Fig. 1 – Effect sizes, measured in standard deviations of separation between low and middle SES group performance, on the composite measures of the seven different neurocognitive systems assessed in this study. Black bars represent effect sizes for statistically significant effects; gray bars represent effect sizes for nonsignificant effects.

Turning to the neurocognitive systems about which specific hypotheses had not been framed in advance, significance levels should be evaluated in light of the number of comparisons being carried out. Children's performance on the Medial temporal/Memory composite was very significantly related to their SES, $t=3.39$, $p=.001$. The other two systems, Parietal/Spatial cognition and Occipitotemporal/Visual cognition, showed trends in the same direction, but these were not significant at even the uncorrected .05 level, $t=1.9$, $p=.062$ and $t=1.21$, $p=.231$, respectively. Of course, with a larger sample, these differences might also reach significance.

In summary, the neurocognitive abilities of healthy, age-, gender- and ethnicity-matched children of low and middle SES were analyzed in a variety of ways, with the following conclusions. The association between SES and neurocognitive development is highly significant and varies significantly in strength across the neurocognitive systems tested. SES disparities in language and memory ability are most pronounced. Working memory ability also differs, along with a weaker trend toward differing cognitive control ability. Visual and spatial cognition were not found to differ significantly in this sample.

3. Discussion

The present study was an attempt to bridge two traditionally separate fields of study, cognitive neuroscience and sociology. Although one might not expect that a construct as complex and imprecise as SES would yield any systematic generalizations concerning brain function, our results indicate that

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[1] Analyses were carried out both with and without imputing missing data and produced similar results. The statistics reported here are based on the original data set, i.e., without imputing values for missing data.

childhood poverty does have reasonably specific neurocognitive correlates. That is, cognitive ability is not depressed across the board among children of low SES. Rather, abilities that have been linked to specific neurocognitive systems are disproportionately affected. We found SES disparities in working memory, cognitive control and especially in language and memory. In contrast, reward processing and visual cognition were not significantly different between the low and middle SES children of this study.

Among our a priori predictions were disparities in Prefrontal/Executive systems. In contrast to previous work, the present study enabled the separate assessment of three aspects of prefrontal function. Two of the three assessed showed SES disparities in our sample. Working memory ability and cognitive control both appeared better developed in the middle SES children. This is consistent with, and expands upon, the finding of Mezzacappa (2004) concerning what he termed "executive attention," which is operationalized in the Attention Network Test as the ability to resolve response conflict and is hence closely related to what we term cognitive control. The consequences of SES disparities in working memory and cognitive control may be substantial, given recent research showing relations between these systems and general fluid intelligence (see Gray and Thompson, 2004 for a review). It is worth noting that language, which also differed between low and middle SES, depends on a distributed system of left perisylvian brain regions that includes left prefrontal cortex.

In contrast, the low and middle SES children performed about the same in tests of reward processing of the kind that depend on ventromedial prefrontal cortex. This was true of two tasks, which tapped reward processing in substantially different ways, in one case by requiring the children to unlearn a series of initial associations between stimulus properties and reward value (known as "reversal learning") and in the other by requiring children to delay their actions in pursuit of rewards. The previous study of kindergarteners included a different measure of ventromedial reward processing within its prefrontal composite, the future discounting of reward. The children were offered one sticker immediately or multiple stickers following a delay. Low and middle SES children were identical in their preference for larger future rewards, with 23 of the 30 children in each group preferring the larger future reward on average (Noble et al., 2005).

If ability to resist impulse and appreciate the value of future rewards does increase with SES as has been suggested (Banfield, 1968; Lewis, 1965), our results suggest that this correlation emerges after childhood, perhaps as a pragmatic adaptation to the contingencies of adult life rather than as a result of childhood SES influences on prefrontal cortex. Indeed, Fuster (2002) points out that the ventromedial regions of prefrontal cortex mature earlier than other regions and might therefore be less sensitive to childhood experience.

Our results add to the literature on SES disparities in cognitive achievement by showing that childhood poverty is associated with a particular profile of neurocognitive strengths and weaknesses. The present study was not intended to identify the causes of the SES disparities found here. Given the complex nature of SES and its correlates, the list of possible causes is long, including: physical health factors such as prenatal care, nutrition and lead exposure; psychological factors such as stress, parental availability and childrearing practices; and genetic factors. Previous studies of SES disparities in cognitive development have either measured none or at most a few of these factors.

The children of the present study were healthy and offered the advantage of an unusually thorough screening for prenatal exposure to illicit substances. We nevertheless cannot rule out physical health factors as contributing to the neurocognitive profile of poverty reported here. Although the children in both of our samples were healthy, it is likely that the middle SES children on average had more varied diets, were exposed to less in utero and second-hand smoke and enjoyed countless other health advantages.

A common misunderstanding regarding the neural bases of cognitive phenomena is that neural bases imply genetic bases. This error is understandable given the use of "hard-wired" as a synonym for "innate," which seems to connote a physical basis more generally in addition to a specifically genetic basis and given the classification of both genetic and neural influences on behavior as "biological" influences. However, any difference in cognitive function, whether genetic or environmental in origin, reflects a difference in brain function, and evidence of specific neurocognitive correlates of SES is therefore neutral with respect to the genetic versus environmental causes of the SES disparities.

As mentioned earlier, SES is correlated with numerous environmental factors that could influence brain development. Furthermore, there is evidence from a number of sources that at least part of the SES disparity in brain development is environmental in origin. A cross-SES adoption study indicated that about half the SES disparity in IQ is genetic in origin, with the other half attributable to some combination of physical and psychological aspects of the environment (Capron and Duyme, 1989). Additional evidence for environmental influence comes from the study of when, in a child's life, poverty was experienced. Within a given family that experiences a period of poverty, the effects are greater on siblings who were young during that period (Duncan et al., 1994).

Future research can seek more specific causal factors in the environments of poor children that are responsible for the neurocognitive correlates reported here. Indeed, knowledge of the specific profile of more and less affected neurocognitive systems facilitates the search for causal factors. Unlike disparities in IQ or school achievement, disparities in the performance of tasks that tax-specific neurocognitive systems suggest hypotheses concerning causes.

Decades of neuroscience research with animals have elucidated two major experiential influences on brain development: stress and environmental complexity. Stress is typically produced in the laboratory by prolonged separation of animal pups from the mother and has a negative impact on anatomical and physiological measures of hippocampal development and on memory ability (McEwen, 2000). Stress is more common within low SES families (Dohrenwend, 1973), and low SES children tend to have higher levels of the stress hormone cortisol (e.g., Lupien et al., 2001), which is damaging to the hippocampus. The SES disparity in memory performance found here is consistent with the effects of stress on hippocampal development. Specifically, it suggests a new mechanistic hypothesis concerning SES and neurocognitive development, whereby the inverse relation between early life stress and SES causes the SES disparity in memory ability.

Environmental complexity is typically manipulated in animal studies by providing one group of animals with ample perceptual stimulation, social interaction and opportunity for varied activity and confining the other group to barren individual laboratory cages. Animals reared in complex environments have better brain development by a variety of criteria (e.g., van Praag et al., 2000; Rosenzweig, 2003). Given the well-documented differences in amount of cognitive stimulation available to low and middle SES children, including the number of books and toys they possess, the amount of adult attention they receive and the variety of locations they visit (Bradley et al., 2001), it is possible that some of the same mechanisms may be at work to produce SES disparities in neurocognitive development. The steepest SES gradients in cognitive stimulation concern language, specifically the amount and nature of parental speech to children (Adams, 1998). This suggests a working hypothesis for explaining the other large SES disparity found here, namely language. The hypothesis that differing amounts of linguistic stimulation received by low and middle SES children cause the difference in language ability found here can now be tested.

Knowledge of the neurocognitive profile of poverty may have practical benefits as well, even before the causal factors have been elucidated. It provides more specific targets for intervention programs, allowing us to more precisely address the neurocognitive vulnerabilities of at-risk children. Finally, by characterizing the effects of childhood poverty in terms of the brain systems affected, the public health dimensions of poverty are revealed. This may renew and expand our sense of societal obligation to poor children by reframing the problem as more than mere educational and economic opportunity, extending to the physical integrity of children.

4. Experimental procedures

4.1. *Participants*

Thirty low SES African American children (17 girls) between the ages of 10 and 13 (mean age 11.7, SD = 1.0) were recruited from a cohort of children followed since birth as control subjects for a study of the effects of prenatal cocaine exposure on child development (see e.g., Hurt et al., 1995). They were born of native English speaking mothers with no major psychiatric illness reporting no use of illegal drugs (including barbiturates, benzodiazepines, cocaine, marijuana, opiates) during pregnancy. This was confirmed by negative urine tests of mother and infant for metabolites of barbiturates, benzodiazepines, cocaine and opiates. Children were born at or near term, with a mean gestational age of 39 weeks (SD = 2, none earlier than 34.5 weeks' gestational age) and no asphyxiation. Their average birth weight was 3.14 kg (SD = 0.58). Apgar scores at 1 min averaged 8.3 (SD = 0.84) and at 5 min 8.9 (SD = 0.43). The children were free of significant abnormality on cranial ultrasound and without fetal alcohol syndrome or any other syndrome known to be associated with developmental delay.

The low SES participants had normal neurological examinations at age 6 years and were screened for blood lead levels above 45 μg/dl (home lead reduction initiated if between 20 and 44) with normal physical growth as measured by height, weight and head circumference. At the time of testing, none of the participants had been diagnosed with any psychiatric disorder nor did they appear to the project staff to have any undiagnosed psychiatric disorder. The children's mothers were on state and medical assistance at the time of birth and were of low SES by the criteria of the Hollingshead (1975) Inventory. Although this inventory is 30 years old, which limits its applicability for contemporary SES measurement, especially for job types created since then, the families in the present study were sufficiently distinct in their SES that there was no ambiguity concerning low versus middle SES classification. Since birth, the children have been evaluated at regular intervals (annually or semi-annually) for measurements of growth, development, language and cognitive and social–emotional development (e.g., Hurt et al., 1995, 1997, 1998) and remain of low SES (Hollingshead parental occupation score of 6 or 7, corresponding to semiskilled labor or unskilled/unemployed, respectively, and no tertiary education). The mean Hollingshead employment score at birth was 7 and at time of testing was 6.1 (SD = 1.0), corresponding to jobs such as hospital aide and nail technician. Mean length of education was 10.3 years (SD = 2.0).

Thirty middle SES African American children, matched for gender and age (17 girls, mean age 11.7, SD = 1.0), were recruited from public schools in Philadelphia and Swarthmore, Pennsylvania and Philadelphia Department of Recreation Summer Camps. Criteria were the same as for the low SES group, except that medical history was obtained by parent report and results of tests including urine screens and cranial ultrasound were not available. Note that the effects of unreported medical problems in the middle SES mothers and children would serve to underestimate SES disparities. The SES criteria for this group were Hollingshead parental occupation score of 4, corresponding to jobs such as secretary and bank teller, or lower (i.e., higher status) and a minimum of 2 years of tertiary education. The mean Hollingshead employment score at time of testing was 2.8, corresponding to jobs such as owner of small business and surgical technician (SD = 1.0). The mean length of tertiary education was 5.3 years (SD = 3.1).

4.2. *Procedure*

Neurocognitive functioning was evaluated using a battery of tasks designed to assess seven key neurocognitive systems. These systems were defined jointly by functional and anatomical criteria. For example, the Lateral prefrontal/Working memory system is assessed by tasks that are functionally face-valid for working memory, that is, they require information to be actively held on-line in order to perform the task and for which there is independent anatomical evidence from imaging or lesion studies that lateral prefrontal cortex is centrally involved in the performance of these tasks. For most of the tasks, there is localizing evidence in child and/or adolescent subjects as well as in adults. Rather than validate the localizations with neuroimaging of our participants, which would require on the order of a dozen scans per participant, we chose tasks for which there is clear localizing evidence, cited below.

Of course, a child's whole brain is working as they perform all of these tasks. Our strategy was to select tasks that disproportionately tax particular systems (Temple, 1997). For example, the assessment of syntactic comprehension involves semantic vocabulary knowledge and visual pattern recognition too. However, only widely known words are used and subjects' understanding of these words is verified prior to administering the task. Visual recognition is required because the task involves matching a picture to a spoken sentence, but the pictures are clear and easily recognized and are presented for inspection at a comfortable viewing distance with no time limitations.

As a compromise between extensive sampling of each system's functions with multiple tasks and an assessment that can be carried out within a single session (to minimize no-shows and drop-outs), we selected two representative tasks per system. These were chosen to be as different as possible from one another in terms of stimuli and responses.

4.3. Prefrontal/Executive systems

4.3.1. *Lateral PFC/Working memory*

Lateral PFC/Working memory plays an essential role in many activities that are not tests of memory per se. The ability to hold the present context or goals of a complex task in mind requires working memory.

4.3.1.1. *Spatial working memory*. This task is part of the computerized CANTAB battery working memory assessment, normed for children (Elliott et al., 1997). The subject must search a set of locations, holding in working memory the locations already checked. In functional imaging studies, spatial working memory tasks with similar displays reliably activate lateral prefrontal cortex in children as well as adults (Thomas et al., 1999).

4.3.1.2. *Two-back*. This task involves monitoring a series of letters for a repeat "two-back." Letters are presented for 500 ms each, separated by a 1 s interval. Subjects must continually update their working memory in order to compare the current letter to the one presented two letters back. Imaging studies in adults and children find lateral prefrontal activation with this task (Casey et al., 1995).

4.3.2. *Anterior cingulate cortex/Cognitive control system*

Anterior cingulate cortex/Cognitive control system plays a crucial role in monitoring for conflict between the individual's responses and the desired response and summoning additional attention when needed.

4.3.2.1. *Go–No-Go task*. Children push a response button as soon as possible when any digit appears on the screen, except for the digit 4. The ability to maintain quick responses yet avoid responding to the 4 depends on conflict monitoring. This task activates anterior cingulate, in both children and adults (Casey et al., 1998).

4.3.2.2. *Number Stroop*. In adaptation of the Stroop task, subjects sort cards that bear between one and seven instances of a digit from 1 to 7 (e.g., five "7's"). In the congruent condition, they are timed as they place the cards as quickly as possible in seven wells labeled with the numbers 1–7 on the basis of the digits. The incongruent condition is the same except that the cards must be sorted according to the number of digits (e.g., five "7's" goes into the 5 well). The Stroop effect is the additional time needed in the incongruent compared to the congruent condition. Functional neuroimaging studies have shown that the incongruent condition of the Stroop task activates a network of prefrontal and parietal regions that includes the anterior cingulate cortex (Bush et al., 1998). The same network is activated in children, adolescents and adults, with a developmental trend toward better performance and greater anterior cingulate activity with increasing age (Andleman et al., 2002).

4.3.3. *Ventromedial PFC/Reward processing system*

Ventromedial PFC/Reward processing system underlies our ability to resist the pull of reward stimuli. In laboratory tasks, it is operationalized by pitting the pull of a reward stimulus against the need to withhold or delay a response to avoid loss. The systems of reward-related brain circuitry develop with age but include ventromedial prefrontal cortex in children and adolescents as well as adults (May et al., 2004).

4.3.3.1. *Delay task*. This task, drawn from the Gordon Diagnostic System (Gordon et al., 1996), requires the child to briefly withhold a response in order to earn points. Originally used in the animal learning literature, this task is sensitive to ventromedial prefrontal function (Mobini et al., 2002).

4.3.3.2. *Reversal learning*. The ability to "unlearn" the previous association between a stimulus and reward is assessed by performance in the intradimensional shift condition of the CANTAB ID/ED Shift task. Reversal learning is impaired in humans after damage to ventromedial cortex (Fellows and Farah, 2003).

4.4. Nonexecutive systems

4.4.1. *Occipitotemporal/Pattern vision system*

Occipitotemporal/Pattern vision system subserves the segmentation and recognition of shapes.

4.4.1.1. *Shape detection*. Adapted from Warrington and James' (1991) Visual Object and Space Perception Battery, the task requires detection of an x in visual noise, displayed on the computer for 2 s followed by a pattern mask. Visual agnosic patients, who are not blind but have damage to higher level visual association cortices in the occipital and inferior temporal regions, are impaired (e.g., Milner and Goodale, 1995) even when the lesions are sustained early in life (Kiper et al., 2002).

4.4.1.2. *Face perception*. Adapted from Mooney's (1957) test of visual closure, faces depicted with shadows in high contrast black and white are presented on a computer screen until the child responds whether the face is upright or upside down.

The ability to perceive Mooney faces is particularly compromised in visual agnosia following inferior occipitotemporal damage (Farah, 2004), and this region is activated during face perception in both adults and children of the age tested here (Aylward et al., 2005).

4.4.2. *Parietal/Spatial cognition system*

Parietal/Spatial cognition system subserves the representation and manipulation of spatial information. In contrast to the pattern recognition functions of the visual system, which are localized in ventral visual areas, the spatial functions are localized more dorsally in the posterior parietal areas of adults and children (Johnson et al., 2001).

4.4.3. *Line orientation*

This test, adapted from clinical neuropsychology, requires the subject to judge the orientation of pairs of line segments, selecting the corresponding orientations from a response display of 11 labeled, radially arranged lines. This is a relatively pure test of spatial perception, with minimal demands on pattern recognition, and it is most impaired by lesions to the parietal cortex in humans (Walsh, 1978).

4.4.4. *Mental rotation*

Pairs of geometric figures from the Ekstrom et al. (1976) kit of factor-referenced tests were presented by computer, and the subject's task was to determine whether they are the same despite orientation differences or different. Cardboard manipulatives were used in explaining the task. Mental rotation is strongly linked to the posterior parietal lobes in children as well as adults (Booth et al., 2001).

4.4.5. *Medial temporal/Memory system*

Medial temporal/Memory system is required for one trial learning. Most standard memory tests are sensitive to both medial temporal and prefrontal function because performance is influenced by the subject's ability to organize the material to be learned and apply mnemonic strategies. We used incidental learning tests, in which the subject does not know that a memory test is coming when the to-be-remembered stimuli are presented, in order to obtain a relatively pure measure of learning ability. The medial temporal lobe, and specifically the hippocampus, is essential for the acquisition of new memory in children as well as adults (Vargha-Khadem et al., 2001).

4.4.5.1. Incidental word learning. In the word learning task, the child views pairs of pictures, presented one pair on a page, and must point to the one named aloud by the experimenter. During the "test" phase, the child listens to a list of words and must decide which items were viewed earlier. Patients with medial temporal damage do poorly on incidental word learning (Mayes et al., 1978).

4.4.5.2. Incidental face learning. This task is analogous to the task with words, except that the learning set stimuli are photographs of faces and the exposure to the initial set takes place while participants judge the faces to be older or younger than 30 years. Medial temporal damage also impairs incidental learning of visual materials, including faces (Mayes et al., 1980).

4.4.6. *Left perisylvian/Language system*

Left perisylvian/Language system is the most complex system studied here. The pair of tasks included here taps the two main and distinct cognitive components of language ability, lexical semantics and syntax. We assessed these with well-known and age-appropriate instruments. As in adults, in children. these abilities depend on a network of areas spanning left perisylvian cortex (Sachs and Gaillard, 2003).

4.4.6.1. Peabody Picture Vocabulary Test (PPVT). This is a standardized vocabulary test for children between the ages of 2.5 and 18. On each trial, the child hears a word and must select the corresponding picture from among four choices. Similar word–picture matching tasks used in functional neuroimaging studies also implicate fronto-temporal cortex (e.g., Thompson-Schill et al., 1998).

4.4.6.2. Test of Reception of Grammar (TROG). In this sentence–picture matching task designed by Bishop (1982), the child hears a sentence and must choose the picture, from a set of four, which depicts the sentence. Its lexical–semantic demands are negligible as the vocabulary is simple and a pre-test ensures that subjects know the meanings of the small set of words that occur in the test. The syntactic abilities tested here localize to perisylvian frontal and temporal cortex (Just et al., 1996).

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