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The Cognitive Phenotype Of Spina Bifida Meningomyelocele

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Abstract

A cognitive phenotype is a product of both assets and deficits that specifies *what* individuals with spina bifida meningomyelocele (SBM) can and cannot do and *why* they can or cannot do it. In this paper, we review the cognitive phenotype of SBM and describe the processing assets and deficits that cut within and across content domains, sensory modality, and material, including studies from our laboratory and other investigations. We discuss some implications of the SBM cognitive phenotype for assessment, rehabilitation, and research.

Keywords

SPINA BIFIDA; COGNITION; ACADEMIC SKILLS

Introduction

A cognitive phenotype – a profile of mental and behavioral skills - is a product of both assets and deficits. Recent investigations have begun to specify *what* individuals with spina bifida meningomyelocele (SBM) can and cannot do, and *why* they can or cannot do it. Within a number of content domains, we have identified particular functions as either intact or impaired, generated hypotheses about underlying processing impairments that cut across content domains, and tested these hypotheses in neurocognitive experiments designed to challenge putative key processing deficits. Delineating the type of processing required for cognitive operations across different content domains, sensory modalities, and material types has helped identify the characteristic cognitive-behavioral strengths and weaknesses associated with SBM and has allowed the neurocognitive profile of SBM to be linked in a principled fashion with the neurobiology of the disorder.

In this paper, we review the cognitive phenotype of SBM and describe the processing assets and deficits, including studies from our laboratory and other investigations. We discuss some implications of the SBM cognitive phenotype for assessment, rehabilitation, and research. The overview in Figure 1 shows neurocognitive assets and deficits, both *domain general core assets and deficits* in timing, attention, and movement and *domain specific functional assets and deficits* in perception, language, literacy, and numeracy. We argue that the cognitive phenotype in SBM is based on neurocognitive processing biases whereby

some types of operations are intact and others impaired, rather than on either absolute or proportionate loss of function (Dennis et al., 2006a).

Domain General Core Assets and Deficits

Timing

Timing and rhythm are essential components of movement and cognition [Ivry and Richardson 2002]. Children with SBM have difficulties in the perception and production of timing and rhythm (Table 1). Perceptual timing deficits are revealed in elevated thresholds for discriminating brief (~400ms) temporal durations. Children with SBM have deficits in perceiving and producing rhythms. For rhythm production, a processing bias favors synchronization (responding in time to an externally paced rhythm) over entrainment (responding in time based on an internally generated model of the rhythm so as to produce the rhythm predictively).

Attention

For *attention*, a processing bias favors internally cued over externally cued attention, a component of which is the development of peripersonal spatial attention. Orienting to the external world and sense of peripersonal space are significantly impaired, even when internally cued attention works relatively well.

Attention includes both stimulus orienting and response control. Stimulus orienting is the automatic capture, disengagement, and shifting of attention to and from salient sensations [Knudsen 2007; Posner and Peterson 1990]. Response control is the voluntary selection of a motor response, a component of executive attention [Posner and Peterson 1990; Rueda et al. 2005].

Children with SBM (Table 2) show relatively deficient stimulus orienting to exogenous (external, from the environment) cues; for instance, they require extra time to detach attention from an exogenous cue, resulting in an increased disengagement cost. Those with a characteristic brain abnormality of SBM, beaking of the midbrain tectum, show attenuated inhibition of return, expressed as a longer time to return to a previously attended cue location compared to a new cue location [Klein 2000]. Exogenous orienting deficits are also apparent in infants and toddlers. Endogenous (internally cued) attention (e.g., negative priming, a longer time to attend to recent ignored stimuli; Tipper, [1992]) appears relatively intact in SBM.

One aspect of spatial attention concerns *peripersonal space*, which is the part of egocentric space, within arm's reach, that is used for activities like picking up objects or drawing [Halligan et al. 2003]. Peripersonal space develops atypically in children with SBM, who differ from their age peers in terms of an exaggerated attentional bias to left hemispace, an abnormal attentional bias to inferior hemispace, and an enhanced Weber fraction, a larger zone of subjective uncertainty about peripersonal space.

Movement

Table 3 shows movement assets and deficits in SBM, in a group of studies using a range of effectors (eyes, hands, arms, and the speech articulatory mechanism). For *movement*, there is a processing bias in both preschoolers and school aged children with SBM that favors motor adaptation and learning over predictive, dynamic motor control.

Domain general core deficits and brain abnormalities

The three core deficits, in timing, attention, and movement, we believe, are a direct consequence of the brain dysmorphologies of the Chiari 11 malformation [Raybaud and Miller 2008; Juranek and Salman, this issue] and associated hydrocephalus [Del Bigio, this issue]. In SBM, deficits in *timing* are related to the volume of the cerebellum [Dennis et al. 2004]; deficits in *attention* are related to the status of the midbrain, posterior cortex, and corpus callosum [Dennis et al. 2005a; Dennis et al. 2005b; Dennis et al. 2005c]; and deficits in movement are related to spinal cord dysfunction and cerebellar dysmorphologies that affect sensory-motor timing and motor regulation.

Domain Specific Functional Deficits

Perception

Current perception models propose two different kinds of spatial relations between observers and objects [Kosslyn 1987]. Categorical perception specifies discrete spatial relationships of visual primitives that may be described by categories (objects), feature groupings (faces), or verbal locatives (e.g., above, below, left, right); coordinate perception specifies precise spatial relations of visual primitives by means of coordinate metric values (e.g., “the line and the dot are 2 cm apart”). Categories and coordinates are basic computational elements for between- and within-category object recognition [Saneyoshi and Michimata 2009]. In perceptual transformations (e.g., mental rotations of objects or reference frames) and multistable states (e.g., a picture with reversible figure and ground), encoding between observers and objects is volatile. Categorical perception is intact in children with SBM, who identify features, gestalts, and relations based on categories or landmarks. Coordinate perception is impaired for illusory perception, pencil-and-paper, and virtual reality tasks. Table 4 shows perception assets and deficits in SBM.

Language

Language is a code by which meaning is expressed by linguistic representations [Dennis 2009]. For *language*, a processing bias favors semantically retrieved over dynamically constructed meaning in SBM. Semantic information based on learned associations can be acquired, but language that must be constructed on-line through iterative cycles of activation, inhibition, and inferencing is impaired. Table 5 shows language assets and deficits.

Pragmatics is concerned with successful functional communication. One form of pragmatic communication is based on social and interpersonal principles like cooperation, turn taking, politeness, and irony; the other is based on textual rhetoric, including ease of processing, clarity, economy, and expressivity [Prideaux 1991]. Interpersonal rhetoric is preserved in children with SBM, who are polite and friendly, sociable, cooperative, and interested in talking. In conversations, they initiate appropriate conversational turns and exchanges, using a mental state vocabulary. However, their textual rhetoric is impaired, and their communication is difficult to process, uneconomic, and unclear.

Syntactic structures assign meaning [Caplan and Hildebrandt 1988] of functional roles (e.g., who is acting, who is being acted on) and *morphology* attaches freestanding function words and inflectional morphemes in words and sentences. *Phonology* refers to the perception and integration [Plante et al. 2006] of features such as vowels, consonants, and syllables that have direct, identifying relationships with utterances. Children with SBM have generally intact syntax, morphology, and phonology.

Semantics is concerned with meaning, literal, idiomatic, and figurative. Semantics is variable in SBM. While semantic information can be activated to facilitate word finding, vocabulary development, and understanding of common idioms, there is impairment in the on-line, iterative cycles of updating and revision of text meanings.

Literacy

Literacy involves coordinated skills that are, in part, developmentally staggered: mastering sound-letter correspondence; sight vocabulary; reading fluency; accessing word and sentence level meaning; and maintaining semantic coherence within and without the text through iterative comprehension cycles [Barnes et al. 2007]. Literacy also involves executive control whereby metacognitive goals affect strategic text processing [van den Broek et al. 2005].

For *literacy* in SBM, a processing bias favors word-level and some sentence-level processing over text-level operations that affects fluency and comprehension for texts. Table 6 shows literacy assets and deficits in SBM.

Children with SBM can read pseudowords, non-words that follow the rules of phonology, evidence of presumptive mastery of the basic rules for representing speech sounds visually. They read single words and have an adequate sight vocabulary. While they can rapidly access the names for written words and pseudowords, their text-level reading fluency is deficient.

For text comprehension, children with SBM activate a range of information within the written text and from semantic memory or world knowledge that facilitates word and sentence comprehension when revision and integration processes are not required. However, they fail to suppress contextually irrelevant meanings and are inefficient in making key inferences within text or between text and knowledge, showing difficulties in on-line iterative revision and integration. Executive control of text comprehension appears to be relatively intact in children with SBM, who can adjust the depth of their text processing to match higher-order strategic goals and accurately judge how well they have understood what they have read.

Numeracy

Beginning in the preschool years with the acquisition of basic grouping, subitizing and counting skills, children gradually acquire the ability to perform operations on number, such as addition and division, and to apply number skills such as estimating, comparing, and problem solving [Mazzocco 2009]. For *numeracy* in SBM, a processing bias favors procedural operations over *de novo* and relational processes that require the integration and application of mathematical information. Basic enumeration and calculation are acquired, albeit slowly, but estimation, problem solving, and mental calculation are impaired. Table 7 shows numeracy assets and deficits in SBM.

Enumeration skills are acquired in SBM, although development appears to be protracted. Preschoolers with SBM have difficulties with counting procedures, but school aged children with SBM perform as well as peers on tests tapping knowledge of numbers such as reading numbers, understanding number series, fractions, and the like. Deficits in object-based addition and subtraction involving transformation on quantities are apparent in the preschool years. By school-age, the data on calculation are mixed, with some studies suggesting that accuracy in both single- and multi-digit arithmetic may be a relative asset within the domain of mathematics, with proficiency by middle to late childhood in earlier learned and better practiced operations (e.g., addition, subtraction, multiplication versus division). In contrast, mental computations are deficient both at school age and in adulthood. Math applications

and problem solving based on manipulation of number and quantitative information are consistently impaired from childhood through young adulthood. Executive control of mathematics may be better than expected, and children with SBM can provide accurate reports of their own calculation strategies, suggesting that they have access to how they are solving mathematical problems even when their solution strategies are immature.

Discussion

How can we characterize the SBM cognitive phenotype, outlined above? What are the real-world implications of the SBM cognitive phenotype for everyday function in individuals with SBM and for cognitive and educational rehabilitation of the SBM cognitive phenotype? How does understanding cognition in SBM through experimental studies inform a research agenda for the future?

The SBM cognitive phenotype: associative vs. assembled processing

We have argued elsewhere [Dennis et al. 2006a] that the core of the processing bias in SBM concerns associative versus assembled processing. In SBM, associative processing is relatively intact, while assembled processing is relatively impaired. We do not suggest that processing differences within either individuals or groups with SBM are absolute, but rather, that they constitute systematic processing biases. *Associative Processing* is based on the formation of associations, enhancement, engagement, and categorization. It includes adaptive changes in response to stimulus repetition, as well as the activation and categorization of stimulus information. In individuals with SBM, strengths in associative processing facilitate temporal synchronicity, endogenous attention, adaptive movement, categorical perception, retrieved language, word-level literacy, and numeration and calculation procedures. *Assembled Processing*, in contrast, is based on on-line iterative cycles of activation, disengagement, and integration; it includes the creation of internal feed-forward models to guide performance over time. Weaknesses in assembled processing disrupt temporal entrainment, exogenous attention, predictive movement, coordinate perception, constructed language, text-level literacy, and most types of mathematical problem solving.

Implications of the SBM cognitive phenotype for assessment and rehabilitation

Delineating the SBM cognitive phenotype has several implications for assessment and rehabilitation of cognitive-academic difficulties in individuals with SBM. It promotes a more precise identification and classification of cognitive function; it delineates asset as well as deficits; it hones more global diagnoses to specific treatment plans, pointing the way to more SBM-targeted forms of cognitive and academic rehabilitation; and it focuses a research agenda for the future.

More precise identification and classification of cognitive function—Individuals with SBM have functional assets in timing, attention, movement, perception, language, literacy, and numeracy, as well functional deficits in the same domains. It is misleading, therefore, to classify or diagnose by domain (“Perceptual Deficit,” “Motor Deficit”) because each domain has assets as well as deficits.

Individuals with SBM have functional assets in audition and vision, as well as functional deficits in the same sensory modalities. This means that assets and deficits cannot be classified according to sensory modality (“Visual Processing Deficit”); the fact that the auditory modality has core deficits (in timing, above) and the visual modality has both assets and deficits in perception means that the cognitive phenotype of SBM cannot be explained by a simple dichotomy between intact auditory and deficient visual perception. Nor is it the

case that perceptual deficits in SBM involve inability to perceive wholes rather than parts, or that individuals with SBM have a generic problem in perceptual integration of material because children with SBM are generally able to perceive gestalt forms.

Children with SBM have apparently well developed ordinality (sense of what comes first, second, etc) but poorly developed temporality (sense of how events occur in time). The term ‘temporal sequencing deficit’ applied to a disorder is ambiguous because it is unclear whether the problem is temporal or ordinal. Our data provide evidence for a functional separation of ordinality and temporality [see also Ullén and Bengtsson 2003, for a neural separation]. Practically, children with SBM do not have a temporal sequencing problem, but rather a problem in temporal motor regulation, which we believe is the basis of their functional difficulty with movement control, drawing, and handwriting.

Individuals with SBM have functional assets involving verbal and non-verbal content as well as functional deficits involving the same types of materials. Therefore, it is misleading to classify assets and deficits according to type of material (e.g., “Non-Verbal Learning Disability”) because some non-verbal functions develop well in SBM and some verbal functions develop poorly; further, compared to those with SBM, children assessed as having a Non-Verbal Learning Disability show a different pattern of spatial perception dysfunction [Mammarella et al. 2009].

In short, while children with SBM have widespread cognitive and behavioral difficulties, these are not pervasive within a domain, and do not involve one modality or one type of material. The SBM cognitive phenotype involves a complex pattern of cognitive function not well characterized by current dichotomies.

Delineating both assets and deficits in SBM cognitive-academic function—The cognitive phenotype of SBM involves both assets and deficits. Diagnostic evaluations and assessments often focus on the areas of deficit, yet experimental studies have identified assets in each content and academic domain. The more precise delineation of assets and deficits that is emerging from experimental studies of cognition in SBM is largely unexploited in the design of programs for motor, cognitive, and academic remediation. However, there is some preliminary evidence suggesting that tailoring interventions to these assets and deficits may be effective (e.g., for math) and that basing treatments on an incorrect and incomplete understanding of the core deficit may be ineffective (e.g., for attention).

On a wide variety of different tasks, and between two different conditions in the same virtual reality task, children with SBM can perform categorical but not coordinate perception tasks. That children with SBM have relatively good spatial orientation when they use landmarks provides an avenue for improving their extrapersonal orientation and ability to navigate through their external environment and community.

Clinical motor deficits are obvious in individuals with SBM, until recently, however, the extent of the relatively well developed ability for motor adaptation and learning in eye, arm, and hand in SBM has been underestimated and has not formed an explicit component of programs to improve coordination and handwriting.

Cross-domain training is an underexplored area of rehabilitation in individuals with SBM. In children with SBM, training in physical rotations improves mental rotation skill [Wiedenbauer and Jansen-Osmann 2007].

Honing More Global Diagnostic Groupings Into Specific Treatment Plans

Attention: Approximately one-quarter of children with SBM have reported difficulties in attention [Burmeister et al. 2005; Colvin et al. 2003; Fletcher et al. 2005; Rose and Holmbeck 2007; Vachha and Adams 2005]. Specifying the attention phenotype of SBM with experimental tasks has helped to understand how it overlaps with, and diverges from, the cognitive-behavioral phenotypes in other conditions. For example, individuals with SBM have difficulties with specific attention orienting tasks, such as inhibition of return, that are performed well by those with ADHD [Dennis et al. 2008].

A better understanding of the attention phenotype in SBM helps make sense of some of the treatment outcome data. Children with SBM respond more poorly than children with ADHD to stimulant medication treatment [Davidovitch et al. 1999; Greenhill 2002], suggesting that standard medication treatments for ADHD may be suboptimal for individuals with SBM, whose attention profile does not include the response control deficits that respond well to stimulant medication.

Executive function: Like many neurodevelopmental disorders, SBM is characterized by poor executive function on psychometric tests [Iddon et al. 2004; Rose and Holmbeck 2007] and parent and self-reports [Mahone et al. 2002; Tarazi, Zabel, and Mahone 2008]. However, executive function deficits in SBM are not global. Individuals with SBM perform poorly on some, but not all; executive function measures [Brown et al. 2008]. Children with SBM do not make perseverative errors on the Wisconsin Card Sorting Test, and their poor performance on the Stroop task is due to slow naming speed [Fletcher et al. 1995]. Although children with SBM have difficulties disengaging attention [Dennis et al. 2005a], a key component of executive function, sustained attention, is relatively intact [Swartwout et al. 2008].

Children with SBM exhibit metacognitive control over their academic skills [English et al. in press]. Like typically developing children, they take more time to read when the situation requires it (e.g., for study rather than for fun) and they are accurate judges of their own understanding. Metacognitive control may support academic remediation. In a case series of adolescents with SBM, Coughlin and Montague [in press] showed that a mathematics word problem intervention that involved learning and implementing executive strategies led to improved problem solving both post-intervention and at long-term follow-up, as well as improvements in self-efficacy around math.

Executive function consists of *representations*, structured event complexes [Grafman 2002] that are the basis of skills like metacognition and planning, and *capacity-limited processing resources* like working memory [Dennis 2006]. The cognitive phenotype outlined here is consistent with studies showing that children with SBM have executive dysfunction, but, in SBM, executive representations may be more intact than executive processing resources, and representations like metacognition may be sufficiently functional to scaffold forms of cognitive-academic rehabilitation.

Some issues for a research agenda for the future

Cross-domain investigations: While it is clear that processing biases are related across core and functional domains, details of the relations remain to be specified to shape testable predictions about the nature of cross-domain associations.

Time, space, and number processing are complexly related [Cappelletti et al. 2009], although an association between peripersonal space and number is fairly well established. Numbers are conceptualized with a spatial metaphor (smaller numbers on the left and larger numbers on the right), and numerical information is represented spatially [for a review, see

Umiltà, Priftis, and Zorzi 2009], so common posterior parietal mechanisms may underlie the orientation of attention in physical space and along a mental number line. For instance, patients with right-sided neglect have a leftward bias when bisecting both physical lines and numbers [Pia et al. 2009]; the presentation of stimuli in near or far space modulates spatial attention for the mental number line [Longo and Lourenco 2009]; and the direction of eye movements, left versus right, during arithmetic problem solving maps onto subtraction versus addition using symbols or objects [Knops et al. 2009]. Children with SBM have an exaggerated leftwards bias in peripersonal space; a demonstration that this is related to anomalies in their mental number line might enhance prediction of which children with SBM are most at risk for later math deficits.

Understanding SBM in the spectrum of neurodevelopmental disorders: One productive line of future research is to understand SBM in relation to other disorders, such as 22q11.2 deletion syndrome. SBM and 22q11.2 deletion syndrome have shared and unshared genes, brain, and cognition.

In SBM, the evidence for genetic anomalies concerns the folate and homocysteine pathways. Studying transmission disequilibrium of SNP alleles, Martinez et al. [2009] reported that anomalies in cystathionine-Beta-synthase, dihydrofolate reductase, methylenetetrahydrofolate reductase, and thymidylate synthetase conferred an increased susceptibility to spina bifida. Nickel et al. [1993] reported three patients with sacral or lumbosacral meningocele and congenital heart defects associated with deletion or microdeletion in the DiGeorge critical region (22q11) and a clinical diagnosis.

Both groups have reduced cerebellar volumes. In 22q12.1 deletion syndrome, Eliez et al. [2000] reported reduced cerebral and cerebellar volumes relative to controls, with vermal lobules VI–VII reduced in the midsagittal area [Eliez et al. 2001]. The scaling of cerebellum reduction in SBM is non-linear. Juranek et al. [this issue] found that while total cerebellar volume was significantly reduced in the SBM group relative to controls, after correcting for total cerebellum volume, and relative to controls, the posterior lobe was significantly reduced in SBM, the corpus medullare was not different, and the anterior lobe was significantly enlarged (see Juranek & Salman, this issue).

Cognitively, both disorders have significant problems in processing time, space, and number [Simon 2008]. For 22q11.2 deletion syndrome, the underlying deficit may involve coarse granularity of processing involving reduced resolution of mental representations of spatial and temporal information [Simon 2008]. We have argued in this paper that the underlying deficit in SBM is a processing bias within and across domains according to which certain types of spatial and temporal processing are intact. Specific comparisons on the same neurocognitive tasks have yet to be made, so it is not at this point clear whether the two disorders differ in *granularity of processing*, *type of processing*, or both.

Summary

Experimental investigations of the cognitive phenotype of SBM have been useful in providing a fuller and more nuanced description of cognitive assets and deficits. More generally, these investigations have provided a link to the observed clinical function, psychometric test performance, and academic profile of individuals with SBM. To be sure, much is yet to be learned about the SBM phenotype itself and the sources of variability in how it is expressed within the SBM population. Nevertheless, it provides a framework for ongoing empirical investigations. As a cognitive research agenda moves forward, we will have a better understanding of how to optimize assessment and intervention programs, and, in parallel, develop a fuller understanding of how SBM is positioned within the spectrum of neurodevelopmental disorders.

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Figure 1.
Model of domain general and domain specific assets and deficits.

Table 1**TIMING**

Sensory motor timing

- ① Perception of subsecond time intervals (~400ms) [Dennis et al. 2004]

RhythmSynchronization

- ⑩ Synchronized rhythm production [Dennis et al. 2004]

Entrainment

- ① Entrained rhythm perception [Dennis et al. 2009a; Hopyan-Misakyan et al. 2009; Snow et al. 1994]
 - ① Entrained rhythm production [Dennis et al. 2004]
-

Table 2

ATTENTION

Orienting
<u>To exogenous (external) cues</u>
① Engage attention [Dennis et al. 2005a]
① Inhibition of return [Dennis et al. 2005b]
① Disengage attention [school age children: Dennis et al. 2005a; infants and toddlers: Taylor et al. 2009]
<u>To endogenous (internal) cues</u>
① Focus attention [Dennis et al. 2005a]
⑩ Negative priming [Dennis et al. 2005a]
Peripersonal spatial attention
① Attentional bias to left-right and inferior-superior hemispace [Dennis et al. 2005c]
① Zone of peripersonal spatial uncertainty [Dennis et al. 2005c]

Table 3**MOVEMENT****Eye movements**

- ⑩ Visual fixation [Salman et al. 2009]
- ⑩ Vestibulo-ocular reflex in response to active head motion [Salman et al. 2008]
- ⑩ Saccade accuracy [Salman et al. 2005]
- ⑩ Smooth ocular pursuit generation [Salman et al. 2007]

Motor learning and adaptation

- ⑩ Adapting saccades to backward target displacement [Salman et al. 2006]
- ⑩ Adapting to prism-distorted visual input [Colvin et al. 2003]
- ⑩ Adapting drawing to mirror image [Edelstein et al. 2004]
- ⑩ Adapting ballistic arm movement to changes in relation between movement and vision [Dennis et al. 2006]
- ⑩ Learning manual rotation task [Wiedenbauer and Jansen-Osmann, 2007]

Ballistic movement

- ⑩ Ballistic arm movement [Dennis et al. 2006]

Dynamic motor regulation

- ⑩ Motor reaction time [Dennis et al. 2009b]
- ⑩ Motor speed [Zeiner et al. 1985; Ziviani et al. 1990]
- ⑩ Manual rotation time [Wiedenbauer and Jansen-Osmann 2007]
- ⑩ Limb taxis [Hetherington and Dennis 1999; Jewell et al. 2010; Lomax-Bream et al. 2007]
- ⑩ Speech taxis [Huber-Okraïne et al. 2002]
- ⑩ Diadochokinesis [Jewell et al. 2010]
- ⑩ Eye-hand control [Wills 1993; Lomax-Bream et al. 2007]
- ⑩ Reaching [Norrin et al. 2004]
- ⑩ Fine motor control and dexterity [Fletcher et al. 1995; Lomax-Bream et al. 2007; Zeiner et al. 1985]
- ⑩ Bimanual coordination [Hetherington and Dennis 1999]
- ⑩ Drawing Sandler et al. 1993; Soare and Raimondi 1977]
- ⑩ Drawing a shape from an image in a mirror [Edelstein et al. 2004]
- ⑩ Handwriting [Barnes et al. 2004b; Pearson et al. 1988; Ziviani et al. 1990]
- ⑩ Speech fluency [Fletcher et al. 1995; Huber-Okraïne et al. 2002; Dennis et al. 1987]

Table 4**PERCEPTION****Categorical**Features

- ⑩ Visual illusions of size, area, and length [Dennis et al. 2002]
- ⑩ Auditory pitch category perception[Dennis et al. 2004]
- ⑩ Auditory speech sound perception[Snow et al. 1994]

Gestalts

- ⑩ Forms [Fletcher et al. 1995]
- ⑩ Figures [Hommet et al. 1999]
- ⑩ Faces [Dennis et al. 2002]
- ⑩ Fragmented objects [Dennis et al. 2002]

Sequences

- ⑩ Number-dot sequencing [Prigatano et al. 1983]
- ⑩ Picture sequencing[Hommet et al. 1999]

Relations

- ⑩ Inferences about categorical spatial relations like up-down and left- right [Barnes et al. 2007]
- ⑩ Virtualreality navigation based on spatial landmarks [Wiedenbauer and Jansen-Osmann 2006]

CoordinateMetric

- ⑩ Judgment of line orientation [Fletcher et al. 1995; Dennis et al. 2002]
- ⑩ Geometry [Barnes et al. 2002]
- ⑩ Spatial route finding [Dennis et al. 2002]
- ⑩ Spatial route imaging [Dennis et al. 2002]
- ⑩ Spatial route learning [Simms 1987]
- ⑩ Virtual reality navigation based on spatial coordinates [Wiedenbauer and Jansen-Osmann 2006]

Transformational

- ⑩ Visual form constancy [Fletcher et al. 1995]
- ⑩ Stereopsis [Dennis et al. 2002]
- ⑩ Figure-ground perception [Fletcher et al. 1995; Dennis et al. 2002]
- ⑩ Multistable visual illusions [Dennis et al. 2002]
- ⑩ Egocentric mental rotations [Dennis et al. 2002]
- ⑩ Extrapersonal mental rotations [Wiedenbauer and Jansen-Osmann 2007]
- ⑩ Mental rotation speed [Wiedenbauer and Jansen-Osmann 2007]

Table 5**LANGUAGE****Pragmatics**Interpersonal rhetoric

- ⑩ Sociable, interested in conversations [Spain 1974]
- ⑩ Mental state vocabulary [Dennis et al. 1994]
- ⑩ Uses mental state verbs to indicate perspective shifts [Dennis et al. 1994]

Textual rhetoric

- ⑩ Non-routinized, on-topic, contextually and socially appropriate utterances [Culatta 1980; Culatta and Culatta 1978; Fletcher et al. 2002; Spain 1974; Vachha and Adams 2003]

Syntax

- ⑩ Syntactic development [Spain 1974]
- ⑩ Syntax production [Byrne et al. 1990]
- ⑩ Syntactic complexity [Barnes and Dennis 1998]
- ⑩ Syntactic comprehension [Dennis et al. 1987]

Morphology

- ⑩ Uses inflections and function words [Swisher and Pinsker 1971]

Phonology

- ⑩ Rhyme-cued word finding [Dennis et al. 1987]

SemanticsLiteral meaning

- ⑩ Vocabulary [Barnes and Dennis 1998; Horn et al. 1985; Spain 1974]
- ⑩ Word finding to semantic cues [Dennis et al. 1987]
- ⑩ Verb generation [Dennis et al. 2008]

Figurative meaning

- ⑩ Common idiom comprehension [Huber-Okrainec et al. 2005]

Text meaning

- ⑩ Schematic structure [Dennis et al. 1994]
- ⑩ Understanding of social scripts [Dennis and Barnes 1993]
- ⑩ Coherence, clarity, economy, and plausibility of narratives [Dennis et al. 1994]
- ⑩ Using context to understand idioms [Huber-Okrainec et al. 2005]
- ⑩ Text-based inferences, integrating propositions across segments of text, and suppressing irrelevant semantic information [Barnes et al. 2004a]
- ⑩ Making inferences that link knowledge and text [Barnes and Dennis 1998]
- ⑩ Maintaining mental models of situations in text [Barnes et al. 2007]

Table 6**LITERACY****Phonological processing**

- ⑩ Pseudoword reading accuracy [Barnes and Dennis 1992]
- ⑩ Pseudoword reading fluency [Barnes et al. 2004a]
- ⑩ Phoneme deletion [Fletcher et al. 1995]

Decoding

- ⑩ Word reading accuracy [Barnes and Dennis 1992]
- ⑩ Word reading fluency [Barnes et al. 2004a]
- ⑩ Noun reading fluency [Dennis et al. 2008]

Text comprehensionMemory based processes

- ⑩ Activation of word meaning [Barnes et al. 2004a]
- ⑩ Activation of character motivation and location [Barnes et al. 2007]
- ⑩ Suppression of contextually irrelevant word meaning [Barnes et al. 2004a]
- ⑩ Text-based and knowledge-based inference generation [Barnes and Dennis 1998; Barnes et al. 2004a]
- ⑩ On-line text revision processes [Barnes et al. 2007]
- ⑩ Text-level fluency [English et al. in press]

Strategic processes

- ⑩ Reading goal adjustment [English et al. in press]
- ⑩ Self-monitoring of comprehension [English et al. in press]

Table 7**NUMERACY****Enumeration**Preschoolers

- ⑩ Counting procedures [English et al. 2009]

School-aged children

- ⑩ Numeration [Barnes et al. 2002]
- ⑩ Rational numbers [Barnes et al. 2002]

CalculationPreschoolers

- ⑩ Object-based addition and subtraction accuracy above subitizable range (sums or subtrahends 4 and above) [English et al. 2009]

School-aged children

- ⑩ Single-digit addition and subtraction accuracy [Barnes et al. 2006]
- ⑩ Multi-digit addition and multiplication accuracy [Barnes et al. 2002]
- ⑩ Single-digit addition speed [Barnes et al. 2006]
- ⑩ Multi-digit subtraction [Ayr et al. 2005; Barnes et al. 2006; but see ⑩ Barnes et al. 2002]
- ⑩ Division [Barnes et al. 2002]
- ⑩ Developmental maturity of calculation strategies for single digit addition [Barnes et al. 2006]
- ⑩ Self-reporting of calculation strategies [Barnes et al. 2005]

Adults

- ⑩ Computation accuracy and speed [Dennis and Barnes 2002]

Math applications

- ⑩ Estimating [Barnes et al. 2002]
- ⑩ Problem solving [Barnes et al. 2002]
- ⑩ Adult functional numeracy [Dennis and Barnes 2002]