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COMMENTARY_REPLY (INVITED ONLY)

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Seeing problems that may not exist: A reply to West et al.'s (2018) questioning of the procedural deficit hypothesis

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In a recent paper ("The procedural learning deficit hypothesis of language learning disorders: We see some problems", *Developmental Science*, 2018), West, Vadillo, Shanks, and Hulme (2018) aimed to test the procedural deficit hypothesis (PDH) of specific language impairment (SLI) and dyslexia. This hypothesis proposes that abnormalities of brain structures underlying procedural memory can largely explain SLI, and perhaps developmental dyslexia (Ullman, 2004; Ullman & Pierpont, 2005; see also Nicolson & Fawcett, 2007, 2011).

West et al. examined aspects of declarative and procedural memory in a representative sample of 7- to 8-year-old children, in relation to language, literacy, and mathematical abilities. They emphasized two findings. First, their declarative but not procedural learning measures correlated with language, reading, and math scores. Second, their procedural learning measures demonstrated relatively low reliability. West et al. concluded that their results "seriously question the suggestion that the construct of a 'procedural learning system' can be reliably measured and cast strong doubts on claims from earlier studies that deficits in such a system are related to language learning difficulties" (pg.10).

Their study raises important questions about the nature of procedural learning, how best to measure it, and whether it is related to typical and atypical language and cognition. However, we suggest that there are a number of weaknesses with the study that invalidate their argument.

FINDING #1: THEIR MEASURES OF PROCEDURAL LEARNING DID NOT CORRELATE WITH LANGUAGE (OR READING OR MATH) MEASURES

West et al. is framed as an investigation of the PDH of SLI and dyslexia. However, they examined a *representative* sample of children, who are likely to be mostly typically developing (TD). Thus, although their results could potentially inform procedural learning in typical development, the findings do not provide a test of the PDH.

Moreover, the tasks and analyses they employed throw doubt on whether they even assessed the functionality of procedural memory. Procedural memory is operationalized by the PDH as the implicit learning and memory that relies on a network rooted in the basal ganglia (Evans & Ullman, 2016; Hamrick, Lum, & Ullman, 2018; Ullman, 2004, 2016; Ullman & Pierpont, 2005). Crucially, on this view procedural memory is *not isomorphic* with implicit learning and memory. Rather, it is one among several types of learning and memory that appear to be largely implicit (Ashby, Turner, & Horvitz, 2010; Doyon et al., 2009; Reber, 2013; Squire & Dede, 2015).

Unfortunately, the implicit/explicit and procedural/declarative distinctions are commonly confounded, including by West et al. As a result, most of their (verbal and non-verbal) implicit learning tasks do not clearly probe procedural memory. The Hebb serial-order learning task is an established paradigm for examining repetition learning

Study	Comparison	Unadjusted SMD	Corrected SMD	95% C.I. Lower	95% C.I. Upper
Clark & Lum (2017)	SLI vs. age-matched controls	0.433	1.105	0.227	0.638
Lum et al. (2013)	Dyslexia vs. age-mached controls	0.441	1.139	0.192	0.689

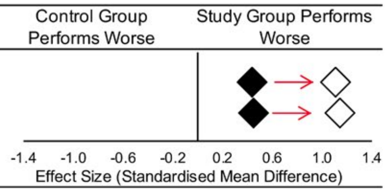

FIGURE 1 Forest plot showing unadjusted effect sizes (diamonds filled in black) and reliability-corrected effect sizes (unfilled diamonds). The figure shows that the impact of correcting for reliability, following Muchinsky's (1996) reliability correction for correlation coefficients, increases the magnitude of the effect size, for two recent relevant meta-analyses. The meta-analysis by Clark and Lum (2017) provides the most recent summary of studies comparing SRT learning between individuals with SLI and TD controls. The metaanalysis by Lum et al. (2013) compared SRT learning differences between individuals with dyslexia and TD controls. For illustrative purposes, the reliability of the SRT task was set to 0.21, which was the lowest reliability found by West et al. for the non-verbal SRT task. The reliability of the tests used to identify children with SLI and dyslexia was set to 0.90. This value roughly corresponds to the internal consistency of the overall composite score used to identify language and reading impairments in most standardized tests of language and reading (e.g., Semel et al., 2004)

(Hebb, 1961; Page & Norris, 2009), but to our knowledge has not been clearly linked to procedural memory, that is, to basal-ganglia–based learning. Worse, the contextual cueing task has been tied to the medial temporal lobe, and thus to declarative memory (Chun & Phelps, 1999; Greene, Gross, Elsinger, & Rao, 2007), which is operationalized as medial-temporal-lobe–based learning, independent of the implicit/explicit distinction (Ullman, 2004, 2016; Ullman & Pierpont, 2005).

The implicit learning of non-verbal perceptual-motor sequences (although not verbal sequences) in SRT tasks has, by contrast, been clearly linked to procedural memory (Clark, Lum, & Ullman, 2014; Hardwick, Rottschy, Miall, & Eickhoff, 2013). However, whereas most SRT studies test for sequence learning by comparing performance between final sequence and random blocks after training on the sequence, West et al. appear to have computed learning as the difference in performance between higher and lower probability sequences *throughout* the task. Their measure of sequence learning thus includes early stages when measurable learning might not yet be robust, as learning in this system is gradual. Moreover, early sequence learning may depend partially on declarative memory (Schendan, Searl, Melrose, & Stern, 2003). Thus, their learning measure decreases the likelihood that sequence learning in procedural memory was reliably measured, reducing the probability that their correlations captured shared variance between procedural learning and language, reading, or math.

FINDING #2: POOR RELIABILITY OF THEIR MEASURES OF PROCEDURAL LEARNING

Although we laud West et al. for examining task reliabilities, their conclusion that poor reliabilities for their (purported) measures of procedural learning "…cast strong doubt…" on results from earlier research on procedural memory in SLI and dyslexia is not warranted. Low reliability attenuates effect sizes (Baugh, 2002), leading to an underestimation of the true effect size and potentially non-significant findings. Thus, a study might observe low effect sizes and non-significant results not because the true effect size is zero, but because the tasks used to measure the outcome variable had poor reliability, leading to a false-negative error.

However, meta-analyses have clearly shown that individuals with SLI or dyslexia perform significantly worse than TD controls on the SRT task (Clark & Lum, 2017; Lum, Conti-Ramsden, Morgan, & Ullman, 2014; Lum, Ullman, & Conti-Ramsden, 2013). Thus, the concern is not whether a false-negative error has been made. Rather, with low SRT reliability, the observed group differences would likely be *underestimations* of the true effect sizes. This can be illustrated by adjusting effect size for reliability (Muchinsky, 1996). Indeed, we see in Figure 1 that correcting for low reliability leads to a *larger* effect size in the difference between TD and SLI/dyslexia, further supporting rather than weakening the PDH.

CONCLUSION

The study by West et al. raises important issues about how best to measure procedural learning and assess its relationship with language, reading, and math development. Because West et al. did not examine language *dys*function and did not clearly probe procedural memory, their findings do not clearly inform the PDH. Additionally, even if their implicit learning measures are taken to reflect learning in procedural memory, low task reliabilities lead to an underestimation of effect sizes, serving to strengthen rather than weaken the evidence that children with SLI or dyslexia are impaired at procedural learning. In sum, rather than calling into question the PDH, we believe their findings serve to illustrate the complexities involved in properly assessing the role of procedural and implicit learning in typical and atypical language, reading, and math development.

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CONFLICT OF INTEREST

There are no conflicts of interest to report.

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