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Probabilistic Category Learning in Developmental Dyslexia: Evidence From Feedback and Paired-Associate Weather Prediction Tasks

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Objective: Developmental dyslexia is presumed to arise from specific phonological impairments. However, an emerging theoretical framework suggests that phonological impairments may be symptoms stemming from an underlying dysfunction of procedural learning. ***Method:*** We tested procedural learning in adults with dyslexia ($n = 15$) and matched-controls ($n = 15$) using 2 versions of the weather prediction task: feedback (FB) and paired-associate (PA). In the FB-based task, participants learned associations between cues and outcomes initially by guessing and subsequently through feedback indicating the correctness of response. In the PA-based learning task, participants viewed the cue and its associated outcome simultaneously without overt response or feedback. In both versions, participants trained across 150 trials. Learning was assessed in a subsequent test without presentation of the outcome, or corrective feedback. ***Results:*** The dyslexia group exhibited impaired learning compared with the control group on both the FB and PA versions of the weather prediction task. ***Conclusions:*** The results indicate that the ability to learn by feedback is not selectively impaired in dyslexia. Rather it seems that the probabilistic nature of the task, shared by the FB and PA versions of the weather prediction task, hampers learning in those with dyslexia. Results are discussed in light of procedural learning impairments among participants with dyslexia.

Keywords: developmental dyslexia, probabilistic category learning, feedback, paired-associate, weather prediction task

Developmental dyslexia is a specific developmental disorder in learning to read, which is not a direct result of impairments in general intelligence, gross neurological deficits, uncorrected visual or auditory problems, emotional disturbances, or inadequate schooling (American Psychiatric Association, 2000). The usual symptoms of dyslexia are difficulties in reading, writing, and spelling, and reading-related subskills such as deficits in word identification and phonological decoding (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Despite decades of intensive research, the underlying biological and cognitive causes of dyslexia remain under debate (for a review see, Démonet, Taylor, & Chaix, 2004).

The phonological account has been one of the prominent theories guiding dyslexia research across four decades. By this account, dyslexia is presumed to arise from a deficit of direct access to, and manipulation of, phonemic language units retrieved from long-term declarative memory (Snowling, 2000). Indeed dyslexia is manifested in poor phonological awareness, impaired verbal short-term memory, and slow lexical retrieval (Vellutino et al., 2004). However, an accumulating body of research is revealing substantial nonlinguistic deficits in those with dyslexia. Dyslexia has been found to be related to deficits in nonlinguistic motor (Nicolson & Fawcett, 1994), procedural learning (Gabay, Schiff, & Vakil, 2012c; Howard, Howard, Japikse, & Eden, 2006; Stoodley, Harrison, & Stein, 2006), and attention skills (Facoetti, Paganoni, & Lorusso, 2000). These impairments are difficult to reconcile with a strictly phonological deficit and have led some to question the ability of the phonological account to serve as the sole explanatory framework of dyslexia (Nicolson & Fawcett, 2011; Stein & Walsh, 1997).

Procedural Learning Deficit in Dyslexia

An emerging perspective in dyslexia research is that a more general deficit, not specific to phonological processing, may underlie dyslexia. The hypothesis is that a selective impairment in procedural learning may result in the difficulties in phonology, reading, writing, and spelling that characterize dyslexia (Specific

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Procedural Learning Deficit, SPLD; Nicolson & Fawcett, 2007, 2010, 2011).

Behavioral studies reveal evidence consistent with procedural learning system impairments among individuals with dyslexia. Much of this work has been carried out in the domain of motor behavior. For example, individuals with dyslexia are impaired in basic motor skills while performing an additional secondary task (Nicolson & Fawcett, 1990; Yap & van der Leij, 1994). Other studies reveal that individuals with dyslexia are impaired on motor adaptation (Brookes, Nicolson, & Fawcett, 2007) and implicit motor sequential learning tasks (Bennett, Romano, Howard, & Howard, 2008; Du & Kelly, 2013; Howard et al., 2006; Stoodley et al., 2006; Stoodley, Ray, Jack, & Stein, 2008; Vicari et al., 2005). Furthermore, procedural motor learning skills of individuals with dyslexia are less stable, are more prone to interference (Gabay, Schiff, & Vakil, 2012b), and consolidate less effectively (Gabay, Schiff, & Vakil, 2012a). In contrast, recent studies suggest that declarative learning might be enhanced among individuals with dyslexia (Hedenius, Ullman, Alm, Jennische, & Persson, 2013).

These impairments are hypothesized to arise from disrupted processing in brain areas related to the procedural learning system (Nicolson & Fawcett, 2011). Evidence from neuropsychological and functional neuroimaging studies supports the distinction between task knowledge that is "declarative" (*knowing what*) and "procedural" (*knowing how*; Cohen, Poldrack, & Eichenbaum, 1997) and suggests that the declarative system is subserved in large part by the medial temporal lobe (especially the hippocampus), whereas neural substrates of the procedural system include the basal ganglia, the cerebellum, and motor-related areas (Cohen et al., 1997; Squire, 2004). In the traditional view, the procedural system has been mainly associated with the learning and formation of motor procedures. However, an accumulating body of evidence implicates this system in learning cognitive, perceptual, and linguistic skills. For example, procedural learning has been implicated in sequence formation (Goschke, Friederici, Kotz, & van Kampen, 2001), probabilistic category learning (Shohamy, Myers, Onlaor, & Gluck, 2004), and perceptual categorization (Maddox & Ashby, 2004; Seger, 2008). It has also been closely tied to formation of grammar rules (Ullman, 2001). Furthermore, subcortical regions such as the basal ganglia have been shown to be involved in phonological processing (De Diego-Balaguer et al., 2008; Pickett, Kuniholm, Protopapas, Friedman, & Lieberman, 1998). In support of the possibility of impairment in the procedural learning system in dyslexia, several neuroimaging studies report cerebellar impairment in individuals with dyslexia (Nicolson et al., 1999; Rae et al., 1998). Recent research has found that the right cerebellum is the brain region that discriminates best between normal readers and individuals with dyslexia (Pernet, Poline, Demonet, & Rousselet, 2009). Other studies have observed atypical basal ganglia activity in those with dyslexia (Brunswick, McCrory, Price, Frith, & Frith, 1999; Kita et al., 2013; Paulesu et al., 1996).

Despite this evidence, the detailed nature of procedural learning impairment in dyslexia is not yet well established. In the present study, we capitalize on probabilistic category learning, which has been widely used in neuropsychological research of procedural learning impairments (Knowlton, Squire, & Gluck, 1994; Knowlton, Squire, Paulsen, Swerdlow, & Swenson, 1996; Shohamy et al., 2004) to examine procedural learning among adults with dyslexia and matched controls. Using a within-participants design, we manipulate the task demands of probabilistic category learning to examine specifically whether individuals with dyslexia are impaired in learning probabilistic cue–outcome relationships and whether the availability of corrective feedback impacts procedural learning among individuals with dyslexia.

Probabilistic Category Learning

Probabilistic category learning is believed to involve procedural learning (Knowlton, Mangels, & Squire, 1996). In probabilistic category learning tasks, participants learn to classify multifeatured stimuli into one of two categories based on trial-by-trial corrective feedback. In a common version of this task, known as the weather prediction task, the cover story involves predicting an outcome, the weather, based on cues conveyed by a set of geometric features presented on four individual cards presented in all possible combinations. An important aspect of the weather prediction task is its probabilistic nature. Namely, the probabilistic relationships between cues and outcomes make it counterproductive for participants to attempt to recall specific previous trials because repetition of any particular configuration of the cues may lead to different outcomes (Eichenbaum, 2010). Declarative memorization is a less useful strategy in the weather prediction task because of this probabilistic relationship between cues and outcomes. Instead, the probabilities associated with particular cues and combinations of cues, acquired gradually across trials much as habits or skills are acquired, are most predictive of outcome. Knowlton et al. demonstrated that people with amnesia due to damage to the medial temporal lobe exhibit intact learning on the weather prediction task, although their declarative knowledge about the learning situation is impaired. On the other hand, patients with basal ganglia disorders such as Parkinson's and Huntington's disease are impaired in learning in the weather prediction task (Knowlton, Squire et al., 1996; Shohamy et al., 2004). This dissociation suggests the significance of the so-called procedural learning system (including basal ganglia) for probabilistic category learning.

Since Knowlton, Squire et al.'s (1996) seminal findings, many studies have investigated the nature of probabilistic category learning among typical individuals and among those with neurological impairments. Across this literature, there is an acknowledgment that both the probabilistic nature of cue–outcome relationships (Knowlton, Mangels et al., 1996) and the presence of experimenter-provided feedback, which is typically provided after each classification response, could affect procedural learning in the weather prediction task. In an effort to dissociate these factors, Shohamy et al. (2004) devised two variants of the weather prediction task. A FB-based task mirrored the typical weather prediction task. In this variant, participants initially guess about the relationship between the probabilistic cues and the outcome and subsequently learn from experimenter-provided feedback about the correct outcome that is signaled by the probabilistic cues. This corrective feedback is eliminated in a paired-associate (PA) variant of the weather prediction task. In this task, participants view a cue and its outcome simultaneously, and learning proceeds through observation. In the PA version of the weather prediction task, no response is required, except to press a key to advance to the next trial. These two variants of the weather prediction task share the demand to learn outcomes signaled by a set of probabilistic cues.

They differ in whether learning takes place by feedback (FB task) or by observation (PA task). Patients with Parkinson's and Huntington's disease are impaired on the FB variant of the weather prediction task, but not on the PA variant (Holl, Wilkinson, Tabrizi, Painold, & Jahanshahi, 2012; Shohamy et al., 2004). This suggests that the ability to learn by corrective feedback is selectively impaired in these diseases (but see Wilkinson, Lagnado, Quallo, & Jahanshahi, 2008, for contradicting results).

More generally and relevant to the present aims, the distinct task demands of the two weather prediction task variants present the possibility of a closer examination of procedural learning dysfunction in dyslexia (Nicolson & Fawcett, 2010). Thus, in the current study, we examine probabilistic category learning in the FB and PA versions of the weather prediction task among dyslexic adults and age- and cognitive ability-matched control participants with normal reading. Our aim is to inform the nature of procedural learning deficits in dyslexia. If the ability to learn from feedback in this procedural learning task is selectively impaired in dyslexia, then we expect selective disruption of probabilistic category learning in the FB variant of the weather prediction task and intact learning in the PA variant. However, each task involves learning across probabilistic input. Therefore, if the procedural learning impairment in dyslexia is characterized by difficulty in learning across probabilistic input, then we expect poorer learning, relative to controls, among individuals with dyslexia on both task variants. If probabilistic category learning is unimpaired among dyslexic participants, then performance for dyslexic and control participants should not differ.

Method

Participants

Fifteen participants with developmental dyslexia and a matched control group participated in the study for a total of 30 participants. All were university students in the area of Pittsburgh, PA. All participants were native English speakers with no reported signs of sensory or neurological deficits and came from families with middle to high socioeconomic status. Diagnosis of a comorbid learning disability such as attention deficit/hyperactivity disorder (ADHD) was an exclusion criterion; 2 participants with dyslexia who had severe symptoms and a diagnosis of ADHD were excluded from the sample. One participant with dyslexia had a diagnosis of attention deficit disorder (ADD); her data were included in the sample because her main symptoms were in the reading domain (see general discussion for further details). A well-documented history of dyslexia was the inclusion criterion for the dyslexia group: (a) each individual received a formal diagnosis of dyslexia by a qualified psychologist; (b) each individual's diagnosis was verified by the diagnostic and therapeutic center at their university. As a group, dyslexic individuals differed significantly from matched controls on all literacy measures. The control group was age matched with the dyslexia group, with no reading problems and the same level of cognitive ability (as measured by the Raven's Standard Progressive Matrices [SPM] test; Raven, Court, & Raven 1992). Written informed consent was obtained from all participants. The study was approved by the Institutional Review Board of Carnegie Mellon University, and it was conducted in accordance with the Declaration of Helsinki.

All participants underwent a series of cognitive tests to evaluate general intelligence (as measured by the Raven's SPM tests, verbal working memory (as measured by the forward and backward Digit Span from the Wechsler Adult Intelligence Scale-III [WAIS-III]; Wechsler, 1997), rapid naming (Wolf & Denckla, 2005), and phonological awareness (Spoonerism; Brunswick et al., 1999). In addition, the dyslexia and control groups performed both untimed and timed (fluency) tests of word reading and decoding skills. Participants performed the Word Identification (WI) and Word Attack (WA) subtests form the Woodcock Reading Mastery Test—Revised (WRMT-R; Woodcock, 1987). In addition, participants performed the Sight Word Efficiency, Forms A + B (i.e., rate of word identification) and Phonemic Decoding Efficiency, Forms A + B (i.e., rate of decoding pseudowords) subtests from the Test of Word Reading Efficiency (TOWRE-II; Torgesen, Wagner, & Rashotte, 1999). Details about these standardized tasks are presented in Table 1. Results are shown in Table 2.

Groups did not differ according to age or intelligence. However, the dyslexia group differed significantly from the control group on word reading and decoding skills across both rate and accuracy measures. In addition, the dyslexia group was impaired compared with the control group in three major phonological domains: phonological awareness (Spoonerisms), verbal short-term memory (STM; digit span), and rapid naming (rapid automatized naming, RAN).

It is noted that all participants in the dyslexia group were high functioning university students with dyslexia. Prior studies of dyslexia reveal that such participants exhibit average performance on standardized reading tests (including that of low-frequency words such as word identification from the WRMT-R) but nevertheless differ significantly from matched control groups and continue to present phonological problems that can be assessed by phonological tests such as the Spoonerism test (Wilson & Lesaux, 2001). Our dyslexic participants fit this profile. Each individual had received a former diagnosis of dyslexia by a qualified psychologist. The dyslexia group differed significantly from the control group in all literacy measures and exhibited phonological processing impairments (as indicted by the Spoonerism test), despite average performance on standardized tests. This profile is clearly indicative of a sample of dyslexic adults.

Apparatus and Materials

Testing took place in a sound-attenuated chamber with participants seated directly in front of a computer monitor during the entire experiment. Stimulus presentation and the recording of response time and accuracy were controlled by a computer program (E-PRIME; Schneider, Eschman, & Zuccolotto, 2002). The stimulus material and card arrangements were similar to that used in the study of Holl et al. (2012) and were created from a set of four tarot cards, each with a different geometric pattern (e.g., triangles, circles, diamonds, and squares), arranged horizontally across the middle of the computer screen in black against a white background. See Figure 1.

Each version of the weather prediction task (FB or PA) included 150 trials during the training phase. On each training trial, participants saw a particular arrangement of cards composed of one, two, or three of the four possible tarot cards. Four-card and no-card arrangements were not used; as such, the experiment included 14

Table 1
Psychometric Tests

The following tests were administered according to the test manual instructions:

1. *Raven's SPM test* (Raven, Court, & Raven, 1992)—Nonverbal intelligence was assessed by the Raven's SPM test. This task requires participants to choose the item from the bottom of the figure that would complete the pattern at the top. The maximum raw score is 60. Test reliability coefficient is .9.
2. *Digit span from the WAIS-III* (Wechsler, 1997)—In this task, participants are required to recall the names of the digits presented auditorily in the order they appeared with a maximum of total raw score 28. Task administration is discontinued after a failure to recall two trials with a similar length of digits. Test reliability coefficient is .9.
3. *RAN* (Wolf & Denckla, 2005)—The tasks require oral naming of rows of visually presented exemplars drawn from a constant category (RAN colors, RAN categories, RAN numerals, and RAN letters). It requires not only the retrieval of a familiar phonological code for each stimulus, but also coordination of phonological and visual (color) or orthographic (alphanumeric) information quickly in time. The reliability coefficient of these tests ranges between .98 to .99.
4. *WRMT-R WI and WA subtests* (Woodcock, 1987)—The WI subtest measures participants' ability to accurately pronounce printed English words, ranging from high to low frequency of word occurrence with a maximum of total raw score 106. Test reliability coefficient is .97. The WA subtest assesses participants' ability to read pronounceable nonwords varying in complexity with a maximum total raw score of 45. Test reliability coefficient is .87. Task administration is discontinued when 6 consecutive words are read incorrectly.
5. *Sight Word Efficiency* (i.e., rate of word identification) *and Phonemic Decoding Efficiency* (i.e., rate of decoding pseudowords) *subtests from the TOWRE-II* (Torgesen et al., 1999)—These subtests were used to measure reading rate. The test contains two timed measures of real word reading and pseudoword decoding. Participants are required to read the words aloud as quickly and accurately as possible. The score reflects the total number of words/nonwords read correctly in a fixed 45-s interval. Task administration is discontinued after 45 s. Sight word efficiency maximum raw score is 108. Phonemic decoding efficiency maximum raw core is 65. Test–retest reliability coefficients for these subtests are .91 and .90, respectively.
6. *Spoonerism Test* (adapted from Brunswick et al., 1999)—This test assesses the participants' ability to segment single syllable words and then to synthesize the segments to provide new words. For example, the word pair "Basket Lemon" become "Lasket Bemon." The maximum raw score is 12.

Note. SPM = Raven's Standard Progressive Matrices; WAIS-III = Wechsler Adult Intelligence Scale-III; RAN = rapid automatized naming; WRMT-R WI = Woodcock Reading Mastery Test - Word Identification; WRMT-R WA = Woodcock Reading Mastery Test - Word Attack.

possible card arrangements. Each arrangement was associated with one of the two weather outcomes (rainy or fine). Overall, outcomes were presented with equal frequency. Each individual card was associated with a particular outcome with a fixed, independent probability. The probability assigned to each card was counterbalanced, and the probability of an outcome on a particular trial was based on the combined probability of the presented cards (see Table 3). Two cards were predictive of fine weather: one strongly (card 4), one weakly (card 3). Two cards were predictive of rainy weather: one strongly (card 1), one weakly (card 2). Overall, participants experienced similar card arrangements, but due to the probabilistic nature of the task, the actual outcomes could differ slightly across participants.

Each participant completed the weather prediction task under two different conditions (FB, PA). Thus, two parallel versions of the weather prediction task were employed with different types of cards and different binary outcomes: either rainy and fine or cold and hot. For half of the participants in each group, rainy/fine were the two possible outcomes in the FB condition, and cold/hot were the outcomes in the PA condition. The remaining participants experienced the reversed pairing. In addition to the set of cards defined by the arrangement of triangles, circles, diamonds, and squares, three additional sets of the four tarot cards were also employed during the experiment, with 25% of participants in each group being trained on each set per weather prediction task variant

Table 2
Demographic and Psychometric Data of Dyslexia and Control Groups

	Group					
Measure	Dyslexia Mean (*SD*)	Range	Control Mean (*SD*)	Range	*p*	Cohen's *d*
Age (in years)	21.26 (3.64)	18–30	21.6 (2.94)	18–30	*ns*	.1
Raven's SPM	79.4 (17.51)	45–95	85.06 (13.08)	50–95	*ns*	.5
Digit span[a] (combined)	10.73 (2.54)	1–12	14 (2.56)	4–12	<.01	.9
RAN objects[a]	104.4 (19.22)	74–129	117.53 (10.73)	93–133	<.05	.8
RAN colors[a]	99.53 (13.3)	80–124	112.4 (6.36)	101–124	<.01	1.2
RAN numbers[a]	103.6 (5.5)	95–113	114.13 (4.24)	107–120	<.01	1.6
RAN letters[a]	102.92 (6.21)	85–111	112.53 (4.37)	105–117	<.01	1.9
WRMT-R WI[a]	96.26 (3.53)	91–103	101.85 (2.58)	95–105	<.01	1.6
WRMT-R WA[a]	99.4 (5.36)	92–113	112 (7.79)	100–126	<.01	1.9
TOWRE-II SA (A + B)[a]	97.66 (8.28)	87–115	117 (12.68)	100–137	<.01	1.88
TOWRE-II PD (A + B)[a]	90.933 (9.19)	72–112	113.2 (8.86)	100–127	<.01	2.7
Spoonerism time	136.44 (41.84)	82–224	90.46 (26.06)	63–150	<.01	.6
Spoonerism accuracy	8.466 (3.37)	1–12	11.06 (2.21)	4–12	<.05	.9

Note. SPM = Raven's Standard Progressive Matrices; RAN = rapid automatized naming; WRMT-R WI = Woodcock Reading Mastery Test - Word Identification; WRMT-R WA = Woodcock Reading Mastery Test - Word Attack; TOWRE-II = Test of Word Reading Efficiency.
[a] Standard scores (whereby smaller numbers are expected for the dyslexic group), other scores are raw scores. Raven scores are presented in percentiles.

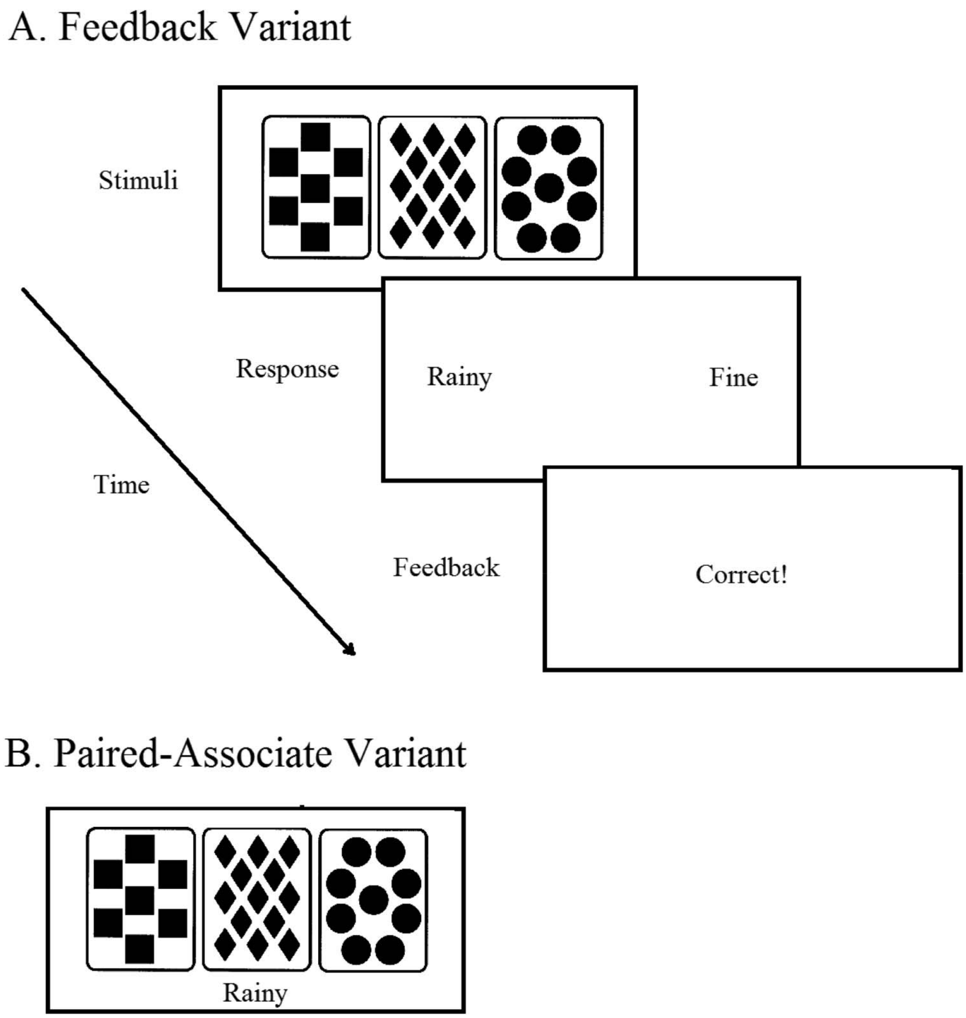

Figure 1. Schematic illustration of the stimuli and tasks.

(FB vs. PA) and with the constraint that participants were trained on a different set of cards in each condition.

Procedure

The procedure was similar to that of Holl et al. (2012). Participants performed both the FB and PA tasks one after the other. Task order was counterbalanced across participants.

Weather Prediction Task—FB Variant

The training phase consisted of three blocks of 50 trials. On each trial, participants saw an arrangement of cards and made a response to predict the weather (rainy/fine or hot/cold). Feedback appeared immediately after a response, with a written indication presented on the screen to convey whether the weather prediction was correct or incorrect. Participants then requested the next trial with a key press; hence, the task was self-paced. The test phase comprised a further 42 trials with the same structure. On these self-paced trials, participants predicted the weather but did not receive feedback.

Weather Prediction Task—PA Variant

The training phase consisted of three blocks of 50 trials. On each trial, participants saw an arrangement of cards along with its weather outcome (rainy/fine or hot/cold). No classification response was required. Participants then requested the next trial, eliciting the appearance of the next card arrangement, along with its weather outcome; hence, the task was self-paced. The test phase was identical to the test phase in the FB version.

Awareness Tests

Both FB and PA tasks were followed by tests of awareness. Lagnado, Newell, Kahan, and Shanks (2006) differentiate between participants' insight into the structure of the task (task-knowledge) and participants' insight into their own judgmental processes (self-insight). Importantly, the two types of awareness do not necessarily agree. A participant may have an incorrect model of the task, but an accurate model of her own judgments.

Table 3
Probability Structure of the Task

Pattern	Cue 1	2	3	4	*p* (cue combination) *p* (pattern)	Frequency (Number per 200 trials)	*p* (outcome)
A	0	0	0	1	0.0095	19	0.89
B	0	0	1	0	0.045	9	0.78
C	0	0	1	1	0.130	26	0.92
D	0	1	0	0	0.045	9	0.22
E	0	1	1	1	0.060	12	0.83
F	0	1	1	0	0.030	6	0.50
G	0	1	1	0	0.095	19	0.89
H	1	0	0	0	0.095	19	0.11
I	1	0	0	1	0.030	6	0.50
J	1	0	1	0	0.060	12	0.17
K	1	0	1	1	0.045	9	0.55
L	1	1	0	1	0.130	26	0.08
M	1	1	0	1	0.045	9	0.44
N	1	1	1	0	0.095	19	0.11
Total					1.00	200	

Note. On any trial, 1 of 14 possible combinations of four cues could appear with the probability indicated, *p*(pattern). Each combination of cues predicted one outcome with the probability *p*(outcome) and predicted the other outcome with a probability of 1 − *p*(outcome).

Task Knowledge

Participants rated how related each card was to the weather outcome using a continuous scale ranging from 0 to 100 (e.g., 0 = definitely rainy, 50 = could be either rainy or fine, and 100 = definitely fine). After participants made a vocal response, the experimenter typed the response on the keyboard.

Self-Insight

Participants then indicated how important each card was for their weather predictions by rating its importance along a continuous scale ranging from 0 to 100, with 0 = not important at all, 50 = moderately important, 100 = very important. The experimenter typed the participant's vocal response on the keyboard.

Results

FB Versus PA Test Phase

We first compared the accuracy of the two groups during the test phase of the FB and PA tasks. Following prior studies using the weather prediction task, the correct answer was determined according to the most probable outcome (Gluck, Shohamy, & Myers, 2002).

Preliminary analysis revealed that the order in which the two tasks were performed did not interact with the group variable, $F < 1$. Therefore, further analyses collapsed data across order. An analysis of variance (ANOVA) was conducted with task (FB vs. PA) as a within-subjects factor and group (dyslexia vs. control) as a between-subjects factor, and the mean proportion of correct weather predictions during the test phase was the dependent variable. Results are presented in Figure 2. The main effect of group was significant, $F(1, 28) = 7.51$, $p = .011$, $\eta_p^2 = .204$, indicating that test-phase accuracy of the dyslexia group ($M = .78$, $SE = .02$) was poorer than that of the control group ($M = .86$, $SE = .01$). There was no main effect of task, $F(1, 28) = 1.72$, $p = .203$, $\eta_p^2 = .054$, and no task × group interaction, $F(1, 28) = .343$, $p = .563$, $\eta_p^2 = .16$. Overall, this indicates an impairment of the dyslexia group relative to the control group on probabilistic category learning. Moreover, the degree of impairment relative to age- and cognitive ability-matched control participants was statistically equivalent across FB and PA versions of the weather prediction task.

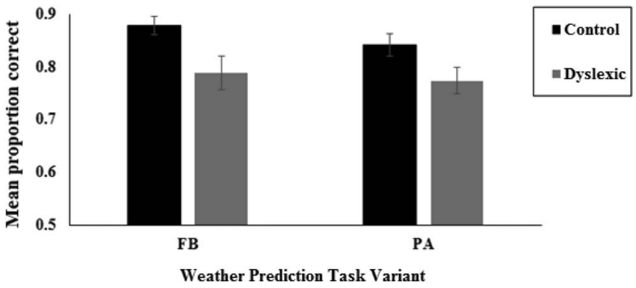

Figure 2. Learning performance measured by mean proportion correct weather prediction accuracy during FB and PA tests of the weather prediction task for the dyslexia and control groups. Error bars represent standard errors.

FB-Based Learning Across Training-Trial Blocks

We also compared the learning curve of the dyslexia and control groups on the FB task. (Note that the learning curve for the PA could not be evaluated because learning took place via observation, and no response was required during training.) An ANOVA was conducted with block (Trials 1–50, 51–100, 101–150) as a within-subjects factor and group (dyslexia vs. control) as a between-subjects factor, and mean proportion correct weather predictions during the learning phase as the dependent variable. Results are presented in Figure 3. There was a significant main effect of group, $F(1, 28) = 4.6$, $p = .0461$, $\eta_p^2 = .13$. The dyslexia group was significantly less accurate ($M = .71$, $SE = .02$) compared with the control group ($M = .77$, $SE = .01$) in response to the training trials on the FB version of the weather prediction task. There was a significant main effect of block, $F(2, 56) = 33.10$, $p = .001$, $\eta_p^2 = .54$, indicating that participants improved at predicting the weather across trials. The group × block inter-

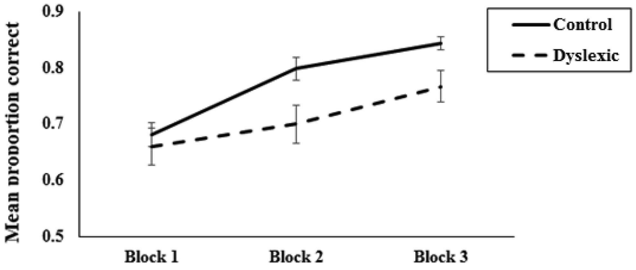

Figure 3. Learning performance measured by mean proportion correct weather predictions during training of the FB task for the dyslexia and control groups. Error bars represent standard errors.

action was marginally significant, $F(2, 56) = 2.92$, $p = .062$, $\eta_p^2 = .08$.

We conducted a further analysis to assure that this marginally significant interaction did not suggest that the observed main effect of group arose from a fundamental difference in the baseline performance of dyslexia versus control group participants instead of a difference in learning across training. The analysis focused on performance on the first 50 training trials in the FB-version of the weather prediction task across groups. An ANOVA was conducted with the first 50 trials binned into 10-trial sets (1–5) as a within-subjects factor and group (dyslexia vs. control) as a between-subjects factor, and mean proportion correct weather predictions across the first five sets of 10 trials (1–10, 11–20, 21–40, 41–50) of the FB weather prediction task as the dependent variable. There was marginally significant main effect for the 10-trial sets, $F(4, 112) = 2.44$, $p = .0507$, $\eta_p^2 = .07$, consistent with modest improvement across these 50 trials. Of most importance, there were no interactions with group, $F(4, 112) = .444$, $p = .775$, $\eta_p^2 = .015$, and the main effect of group was nonsignificant, $F(1, 28) = .064$, $p = .801$, $\eta_p^2 = 08$. This reassures that the omnibus group main effect across the entire set of training trials was not driven by an a priori group difference instead of a difference in learning within the probabilistic category learning task.

Analysis of Response Strategy

In order to examine if the two experimental groups used different strategies while performing the FB variant of the weather prediction task (in the PA version there was no manual response during learning phase, so strategies cannot be assessed), we followed the analysis of Gluck et al. (2002). We examined which of three possible strategies accounts best for participants' responses: (a) an optimal multicue strategy, in which participants respond to each pattern on the basis of associations of all four cues with each outcome; (b) a one-cue strategy, in which participants respond on the basis of presence or absence of a single cue, disregarding all other cues; or (c) a singleton strategy, in which participants learn only about the four patterns that have only one cue present and all others absent. A nonparametric χ^2 analysis indicated no significant group differences in the number of participants optimally assigned to each strategy, $\chi^2(1) = 0$, $p = 1$; $\chi^2(1) = 1.3$, $p = .24$; $\chi^2(1) = 0$, $p = 1$ (for the multicue strategy, one-cue strategy, and singleton strategies, respectively). Thus, there were no significant differences between the groups in preferred response strategy in the FB variant of the task.

Awareness: Task-Knowledge

Mean task knowledge difference scores were calculated across the four cards for each participant. A difference score was calculated for each card following the approach of Newell, Lagnado, and Shanks (2007). This was calculated as the actual probability of the negative outcome (.2, .4, .6, .8, for cards 1–4, respectively) subtracted from a participant's own subjective probability estimate. A positive score is indicative of probability overestimates whereas a negative score is indicative of probability underestimation. Preliminary analysis revealed no significant main effects or interactions with the order in which the task-knowledge tasks were performed across FB and PA tasks (minimum $p = .168$). Therefore, the data were collapsed across task presentation order. An ANOVA was conducted on the mean difference scores with task (FB vs. PA) as a within-subjects factor, and group (dyslexia vs. control) as a between-subjects factor. Figure 4 presents task knowledge difference scores for FB and PA tasks for each group. Overall, there was a significant main effect of group, $F(1, 27) = 8.51$, $p = .003$, $\eta_p^2 = .233$. This effect was not modulated by card strength. Task knowledge of the dyslexia group on both the FB, $t(14) = -2.43$, $p < .05$, and PA, $t(14) = -3.92$, $p < .01$, tasks differed significantly from zero whereas task knowledge of the control group did not differ from zero for either the FB, $t(14) = .86$, $p = .403$, or the PA, $t(14) = 1.37$, $p = .18$, task. This pattern of results indicates that the control group was accurate at determining probabilities whereas the dyslexia group significantly underestimated the actual probabilities. All other effects were nonsignificant, $F < 1$.

Awareness: Self-Insight

The main test of self-insight awareness is whether participants' ratings discriminate between strongly and weakly predictive cards. Ratings for two strongly predictive cards (cards 1, 4) were combined, and ratings for the two weakly predictive cards (cards 2, 3) were combined. Preliminary analysis revealed no significant main effects or interactions with the order in which the self-insight tasks were performed across FB and PA tasks (minimum $p = .127$). The results, therefore, were analyzed across order. An ANOVA was conducted on ratings, with task (FB vs. PA) and strength of association between card and outcome (strong vs. weak) as within-subjects factors and group (dyslexia vs. control) as a between-subjects factor. Figure 5 presents participant's ratings for strongly and weakly predictive cards for the FB and PA tasks for each group. There was a significant main effect for card strength, $F(1, 27) = 47.54$, $p = .000$, $\eta_p^2 = .14$, indicating that participants gave higher importance ratings to strong cards compared with weak cards. There was also a marginally significant interaction of strength of association and task, $F(1, 27) = 3.81$, $p = .061$, $\eta_p^2 = .11$, such that the tendency to rate strong cards was greater in the FB task compared with the PA task. All other effects were nonsignificant. There were no significant group differences.

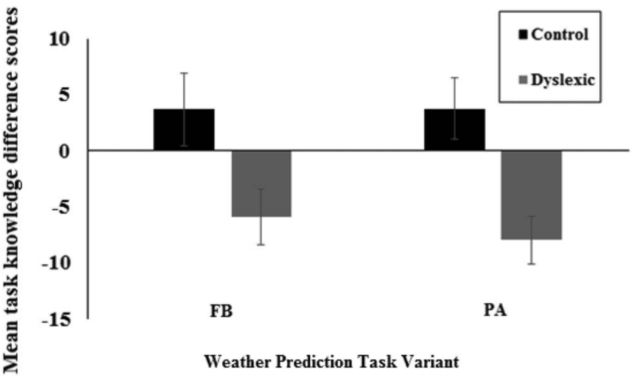

Figure 4. Mean task knowledge difference scores for the dyslexia and control groups (a). Error bars represent standard errors. FB = feedback; PA = paired-associate.

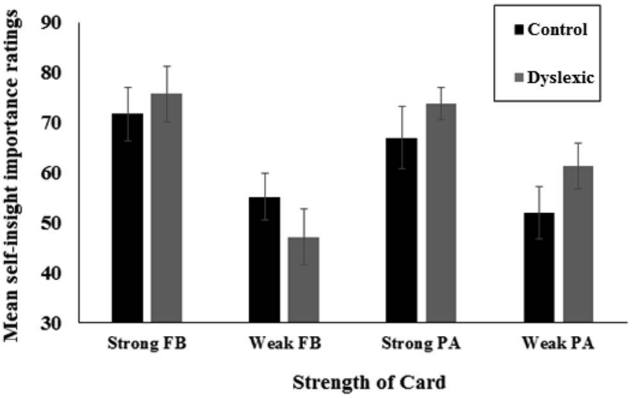

Figure 5. Mean self-insight ratings for strong and weak cards for dyslexia and control groups. Error bars represent standard errors. FB = feedback; PA = paired-associate.

General Discussion

To the best of our knowledge, the present study is the first observe impairments in probabilistic category learning among participants with dyslexia. We examined two versions of the weather prediction task that shared the probabilistic association of cues and outcomes, but differed in whether learning proceeded via explicit feedback (FB version) or through observation of cues and their outcomes (PA version) among a group of adults with dyslexia and matched controls. In other domains, the FB and PA versions of the weather prediction task have served to examine the task characteristics that engage procedural learning (Knowlton et al., 1994; Knowlton, Squire et al., 1996; Shohamy et al., 2004). Both versions of the weather prediction task rely on probabilistic relationships between cues and outcomes. The key difference between the PA and FB versions of the weather prediction task is whether learning takes place via observation (PA) or corrective feedback (FB), but each task requires learning across probabilistic cue–outcome relationships. Comparison of categorization accuracy at test revealed that dyslexic participants learned significantly less than age- and cognitive ability-matched controls in both the FB and PA versions of the weather prediction task. In the FB task, for which responses were gathered during training trials, it was possible to observe impaired performance among participants with dyslexia during the learning phase.

We observed no dissociation of impairment across the FB and PA versions of the weather prediction task among the dyslexic participants in the present study. This suggests that poorer learning among dyslexic participants relative to controls was related to a task characteristic common to FB and PA versions of the weather prediction task: learning across probabilistic cues. Individuals with dyslexia are not specifically impaired in learning from feedback, but rather have difficulty in learning relationships across probabilistic input. In fact, evidence from other procedural learning tasks such as the serial reaction time (RT) task supports this possibility; dyslexic learners are significantly impaired in learning probabilistic sequences (Du & Kelly, 2013; Howard et al., 2006), but not deterministic ones (Deroost et al., 2010; Rüsseler, Gerth, & Münte, 2006). Identification of procedural learning impairments in such high functioning participants indicates the involvement and centrality of procedural learning impairments in the etiology of dyslexia. Further evidence will be necessary to determine whether these impairments extend to younger samples of dyslexics and those with more severe impairments. In all, these results indicate impairment in probabilistic category learning among participants with dyslexia that is not a result of a selective deficit of FB-based learning, since poorer learning relative to control participants was observed across both FB and PA tasks. Future studies should explore the possibility that additional learning trials could bridge the learning gap as the dyslexia group was able to reach to a relatively high level of accuracy on each task at the end of training.

The pattern of awareness rankings for dyslexic and control participants is interesting in this regard. At the end of learning, the control group exhibited explicit task knowledge, as observed in fairly accurate estimates of how well the cues predicted weather outcomes. This is consistent with previous reports that unimpaired participants have good explicit knowledge of the probabilistic relationships learned in the weather prediction task (Holl et al., 2012). However, the dyslexic participants were significantly less accurate in task knowledge, tending to underestimate the probability that particular cues predicted the associated outcomes. This is particularly interesting in light of the fact that dyslexic participants did not differ significantly from the control group in explicit rankings of strongly versus weakly predictive cards in the self-insight awareness task. Both groups rated strongly predictive cards as the more important predictors. The dyslexia group thus accurately ranked the cues according to the predictive value, but nonetheless underestimated how relevant the cue was to predicting the outcome.

The current results are consistent with procedural learning impairments in dyslexia and raise the possibility that probabilistic relations present a particular learning challenge for those with dyslexia. A general impairment in probabilistic learning, not specific to language, may have cascading effects on how language is processed among those with dyslexia because language acquisition and subsequent processing rely heavily on probabilistic mappings from the input. In reading, for example, the co-occurrence of letters can help to predict the next letter in a word, albeit not deterministically (Arciuli & Simpson, 2012). Likewise, transitional probabilities across syllables may help listeners to discover word boundaries in continuous spoken language (Saffran, Aslin, & Newport, 1996). Indeed, the ability to integrate across probabilistic acoustic information is essential in learning to map the substantial signal variability present in spoken language to consistent linguistic units (see Holt & Lotto, 2010). Impairment in the general cognitive mechanisms involved in learning from probabilistic input could be expected to have important repercussions in acquiring and processing linguistic materials due to the high demands language places on learning and using probabilistic relationships. Common with this are the findings of impaired probabilistic category learning in populations with linguistic deficits such as individuals with Specific Language Impairments (Kemény & Lukács, 2010).

Procedural learning impairments have been also implicated in ADHD (Adi-Japha, Fox, & Karni, 2011). Furthermore, basal ganglia/cerebellar abnormalities and specifically disruption to corticostriatal loops have been strongly implicated in ADHD (Berquin et al., 1998; Teicher et al., 2000). Based on this and the high comorbidity between dyslexia and ADHD, there might be concern that patterns observed in the current research originated from attention impairments within the dyslexia group. However, the presence of an additional ADHD comorbid learning disability was an exclusion criterion. Moreover, although one participant with dyslexia that had also been diagnosed with ADD was included in the sample, excluding her from the analysis only strengthened the observed group difference, $F(1, 28) = 8.589$, $p = .007$, $M = .78$ for the dyslexia group, $M = .85$ for the control group. Taken together, this lessens the possibility that attention problems are the driving force behind the present results. Nevertheless, the comorbidity of dyslexia and ADHD remains of interest, and it has been suggested that both ADHD and dyslexia may belong to a family of neurodevelopmental disorders that are associated with procedural learning impairments (Nicolson & Fawcett, 2007; Ullman, 2004). Future studies with both populations will be informative in delineating the nature of procedural learning impairments observed across dyslexia and ADHD.

The task structure of the weather prediction task raises the possibility that the present results may arise from an impairment in PA learning, which has been implicated in dyslexia (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003). In a typical PA learning task, participants are presented with several visual pictures and have to learn the relationship of each image to a real word or nonsense name that is presented auditorily (visual-verbal associations) or to visually presented symbols (visual-visual associations). In visual-verbal PA tasks, participants must repeat the auditorily presented verbal label. Individuals with dyslexia are impaired in learning visual-verbal, but not visual-visual, associations (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003), and visual-verbal PA learning is related to learning to read (Hulme, Goetz, Gooch, Adams, & Snowling, 2007).

It could be argued that learning the association between cue and outcome in the weather prediction task draws on PA learning, which is known to be impaired in dyslexia (Mayringer & Wimmer, 2000; Messbauer & de Jong, 2003). However, although there is superficial similarity between these tasks, the weather prediction task (as used in our study) is arguably more similar to the visual-visual PA learning in which individuals with dyslexia are unimpaired. In the weather prediction task, participants learn an association between visual character (cue presented visually on a card) and outcome (presented orthographically). There is no verbal response, no information is presented auditorily, and there is no nonsense verbal label to retain. This is important as previous research has consistently demonstrated that PA learning that does not involve phonological output is not disrupted in dyslexia (Litt & Nation, 2014) and that only tasks that involve verbal-auditory output are found to be significantly correlated with reading (Litt, de Jong, van Bergen, & Nation, 2013). In fact, Litt et al. (2014) suggest that dyslexics' PA learning impairments do not arise from problems in associative learning per se, but rather from deficits in phonological form learning that is engaged by the auditory-phonological aspects of visual-verbal PA tasks. Since our tasks did not involve a high verbal demand (such as unfamiliar nonsense words presented auditorily to be paired with associated symbols) as is typical in PA learning tasks, it is unlikely that PA learning impairments could account for the current results.

Impaired learning of the relationship of probabilistic nonlinguistic visual cues to outcomes among adults with dyslexia is difficult to reconcile with a purely phonological account, but is consistent with a procedural learning deficit in dyslexia (Nicolson & Fawcett, 2011). However, there remain many important open questions as to the nature of the procedural learning impairment in dyslexia to be answered. Indeed, the wide range of learning tasks considered to be "procedural" is unlikely to draw on identical learning mechanisms. In further development of the taxonomies of deficits observed in dyslexia and other disorders, it will be important to develop more detailed conceptualization of the nature of the tasks that fall into the class of procedural learning. The present results contribute to this by demonstrating that it is the *probabilistic* nature of the weather prediction task that causes difficulty for learners with dyslexia, and not a disruption of FB-based learning.

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