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Abstract

Children with developmental disorders of reading are argued to have procedural learning deficits, such as incompetency to learn sequences. However, the evidence is weak. Learning in procedural system undergoes at least two well-known phases, initial acquisition and later offline consolidation. And, offline sequence learning is less studied in children with reading difficulties. In the present study, we present data on initial and later learning rates of implicit sequences in a group of children with (n=22) and without (n=22) reading difficulties in English whose native language is Kannada, a structurally distinct language to English. Our population is unique and were never studied on their procedural learning. They are unique in the sense that they receive extensive literacy exposure in English (which is their L2) from very early age, however, their oral fluency in L2 and text exposure in L1 are limited. We ran an implicit serial reaction time task to test their learning rates of 10- item visuo-spatial sequences on both initial and later sessions (> 24 & < 48 hours). Findings showed that poor readers showed slower learning rates only on later learning phase, where as their learning rate on initial learning phase was comparable to good readers. Further, learning slopes did not predict literacy scores in either of the groups. The importance of examining the learning processes holistically in children with reading difficulties and the findings' potential contribution to informing the theories arguing procedural learning deficits are discussed.

Keywords	reading difficulties; procedural memory; serial reaction time task; implicit learning; initial phase; consolidation; procedural deficit; Kannada
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Link research data did not work. All materials related to the paper (experiment task, analysis pipeline, script, raw data, summary files) are on OSF and links are given within the manuscript.

Oxford
10th July 2018

Dear Editor
Neuroscience Research

I am here by submitting my paper titled 'Initial and Later Procedural Learning Rates of Implicit Sequences in Good and Poor Readers of English' for considering to be reviewed in *Neuroscience Research*. The paper presents data on procedural memory in a group of poor and good readers of English from India. And, this is the first data set looking at procedural memory in children with reading difficulties in India. The findings are interesting. First, out of two phases of learning (initial and later phases on day 2) examined, the groups differed only on later phase of learning. Second, the learning rates did not predict literacy. I found the work suitable for *Neuroscience Research* given its scope to inform theories of procedural learning in developmental disorders. Note I had difficulty with the upload data while submission. However, within the manuscript the links to open science framework to task used, raw data files, analysis scripts and summary data sets used for models are given in appropriate places.

I look forward to your response

A handwritten signature in blue ink, appearing to read 'S. Kuppuraj', with a stylized flourish at the end.

Kuppuraj Sengottuvel, Newton International Fellow,

University of Oxford

UK

First data set examining procedural memory in good and poor readers of English from India

Poor readers of English differ from good readers only on the later learning phase of procedural learning

Procedural learning rates did not predict literacy scores

Theories arguing procedural learning deficit in children with reading difficulties must be more specific about their predictions for initial and later learning deficits

Initial and Later Procedural Learning Rates of Implicit Sequences in Good and Poor Readers of English

Sengottuvel Kuppuraj^{1*} and Vasudev Arpitha²

¹Newton International Fellow, Department of Experimental Psychology, University of Oxford, UK, kuppuslp@gmail.com (corresponding author)

²Post Graduate in Speech Pathology, All India Institute of Speech and Hearing, Mysore, India, arpithakullal@gmail.com

Abstract

Children with developmental disorders of reading are argued to have procedural learning deficits, such as incompetency to learn sequences. However, the evidence is weak. Learning in procedural system undergoes at least two well-known phases, initial acquisition and later offline consolidation. And, offline sequence learning is less studied in children with reading difficulties. In the present study, we present data on initial and later learning rates of implicit sequences in a group of children with (n=22) and without (n=22) reading difficulties in English whose native language is Kannada, a structurally distinct language to English. Our population is unique and were never studied on their procedural learning. They are unique in the sense that they receive extensive literacy exposure in English (which is their L2) from very early age, however, their oral fluency in L2 and text exposure in L1 are limited. We ran an implicit serial reaction time task to test their learning rates of 10- item visuo-spatial sequences on both initial and later sessions (> 24 & < 48 hours). Findings showed that poor readers showed slower learning rates only on later learning phase, where as their learning rate on initial learning phase was comparable to good readers. Further, learning slopes did not predict literacy scores in either of the groups. The importance of examining the learning processes holistically in children with reading difficulties and the findings' potential contribution to informing the theories arguing procedural learning deficits are discussed.

Keywords: reading difficulties; procedural memory; serial reaction time task; implicit learning; initial phase; consolidation; procedural deficit; Kannada

1. Introduction

Individuals with developmental dyslexia (DD) (or reading disability) have significant difficulty in reading despite appropriate educational opportunities, non-verbal intelligence, and or an identifiable disease or disorder that might otherwise account for the problem (American Psychiatric Association, 2000). A common criterion for diagnosing reading disability is decoding abilities (the accuracy or fluency) of reading aloud greater than 1.5 SD below the standard mean, which results in a prevalence of about 5-10 % (Shaywitz, Shaywitz, Fletcher, & Escobar, 1990) . The cause of the disorder is long debated. One prominent view is that children with reading difficulties have phonological impairments (Bishop & Snowling, 2004) that may result in written word recognition and phonological decoding (using letter-sound mapping knowledge to decode novel words) deficits. Reading difficulty is also associated with other deficits such as working memory (Smith-Spark & Fisk, 2007), executive functions (Brosnan et al., 2002), motor function (R. I. Nicolson, Fawcett, & Dean, 2001), and impairment of serial-order learning that affects language learning and processing (Szmalec, Loncke, Page, & Duyck, 2011). Recent theories have argued that a more general learning deficit may underlie literacy difficulties in DD (Roderick I. Nicolson & Fawcett, 2008). It is a general view that phonological impairments and general learning deficits in DD are not necessarily mutually exclusive, and may be theoretically compatible.

In the present study we investigate the learning performance at two stages- initial (on day 1) and later (on day 2), in one of the less studied general learning systems - procedural memory system, in a unique population from India (see below). Our population is a group of good and poor readers (9-16 years) of English which is not their native language (for ease of description it is stated as their L2 in remainder of the text); nevertheless, their medium of instruction is English dominant. In what follows we define the extra-literacy characteristics of our test population as they may contribute to their reading outcomes (e.g., Hugo, 2014).

1.1. Background of the population

Our participants' native language is Kannada-an agglutinating language of Dravidian family, thus, majority of our participants' parents used Kannada (their L1) as home and work language. Nevertheless, all the children were exposed to English in schools from an early age (< 5 years that is kindergarten onwards), where they read and write all but one subject (which is in Kannada) in English (L2). It should be noted that outside classroom all our participants spoke Kannada, making their English oral language exposure minimal. Further, there are differences between language structure and written sound systems of English and Kannada. Kannada's oral language syntax is word order free, agglutinating, and inflections rich. Sound system in Kannada is alphasyllabery that represents sounds at the level of both the phoneme and the syllable simultaneously (Nag, 2014; Nag, Caravolas, & Snowling, 2010). The cognitive processes underlying reading in Kannada – an alphasyllabery language may depend on both syllabic and phonemic awareness, and English-an alphabetic language may largely depend on phonemic awareness (Nakamura, Koda, & Malatesha Joshi, 2013). However, the influence of text knowledge of Kannada on English, if any, may be subtle in the present population given the lack of exposure to Kannada texts at schools. Given the magnitude (80-90% of texts/ day), duration (starting from kindergarten) of English text exposure, least possible influence from first language reading, the present population may be considered to have favourable environment to master English reading (Lesaux & Siegel, 2003).

The present test population may not fit well with classical diagnostic label of developmental dyslexia (DD) considering that their reading difficulty is not in their L1. And, may not fit well with English as second language readers given that they indeed receive higher text exposure in English than L1 right from very early age. Therefore, henceforth, in the present study, the present population with and without reading difficulties in English would be addressed as poor readers (PR) and good readers (GR) respectively. To our knowledge, there are no published data on procedural learning system of this unique population. Therefore, we review studies that examined procedural memory in DD in general (predominantly in L1 English speakers). It shall be noted that, two studies have examined procedural learning in children with developmental language disorders (DLD)-a comorbid condition of reading difficulties (Bishop & Snowling, 2004) in India, both conducted on Kannada speaking

children. These studies found poor sequence learning in children with DLD (Kuppuraj, Rao, & Bishop, 2016; Sengottuvel & Rao, 2013b).

1.2. Procedural memory and reading

Procedural memory underlies learning and processing of a wide range of perceptual- motor and cognitive skills, tasks, and functions (Ullman, 2001a, 2004, 2016) including sequences such as learning of statistical relationship between two events (Perruchet & Pacton, 2006). An example of statistical ability is, on a temporal sequence such as ‘a-b-a-c’, being sensitive to the fact that the probability of ‘b’ given ‘a’ is 50 %. Learning in this system has also been implicated in learning new, and controlling well-established, motor and cognitive skills (Fletcher et al., 2004). Learning in procedural memory system is gradual, retrieved automatically, and knowledge learned by the procedural learning system is less likely to be explicitly describable. For example, learning to ride a bicycle could be mainly implicit and procedural, therefore, it is hard to verbalize the underlying skill requirements. However, given a bicycle it is easy to show ‘how’ to ride.

Children with DD are argued to have procedural learning deficits (R. I. Nicolson, Fawcett, Brookes, & Needle, 2010; Roderick I. Nicolson & Fawcett, 2007). In reading, the correspondences between arbitrary visual symbols and the sounds sometimes share probabilistic relation. For example, in a language like English the letter “c” often maps onto the phoneme /k/ and sometimes to /s/ depends on following phoneme (i.e., ‘s’ if following phoneme is ‘i’). As per the argument, impairment in procedural system disrupts automatization of skill which is likely to affect grapheme-phoneme conversion, word recognition (Sigurdardottir et al., 2017), and learning orthographic regularities eventually affecting reading. However, correlation between reading proficiency and statistical learning abilities is inconsistent (Correlation: Arciuli & Simpson, 2012; no correlation: Schmalz, Moll, Mulatti, & Schulte-Körne, 2018).

One of the approaches to study implicit sequence learning in DD is to use the serial reaction time (SRT) task (Nissen & Bullemer, 1987). On a typical non-verbal SRT task, on each trial four horizontal circles appear on the screen. Participants are asked to track the location of the stimulus (e.g.

illuminated circle) that appears in one of the circles by pressing the spatially corresponding button on the keyboard as accurate and fast as possible. Two kinds of blocks are presented: random, where the stimulus location is random, and pattern, where, unbeknownst to the participant, the series of locations follows a predetermined repeated pattern. For instance, '132342134142' is a 10 item first order sequence location set where '3' predicts '4' with some probability (i.e., two out of three times or 67%). The usual finding on the participants who learn the patterned sequences is for the reaction time (RT) for pattern blocks to be faster than random blocks.

1.3. Procedural learning: Initial phase

The process of procedural skill acquisition begins with the initial exposure and repeated engagement to a task (Pawlik & Rosenzweig, 2000). This initial phase is called acquisition phase which shows improvements in performance (tracking the predictable location) observable over seconds or minutes (i.e., online learning), followed by asymptote of learning curve (Hauptmann, Reinhart, Brandt, & Karni, 2005). Two subcomponents are argued to contribute to this initial- a 'generalized skill learning' which is the proficiency in executing the RT task by successfully mapping the stimulus to response key locations and 'sequence specific learning' which is the knowledge about the order in which the stimulus location occurs (Ferraro, Balota, & Connor, 1993; Knopman & Nissen, 1991). Of few studies we reviewed that focused on this initial phase of procedural learning in children with DD using SRT task, some showed impaired learning in children with DD compared to typical readers (Gabay, Schiff, & Vakil, 2012);(Howard, Howard, Japikse, & Eden, 2006; Jiménez-Fernández, Vaquero, Jiménez, & Defior, 2011; Lum, Conti-Ramsden, & Ullman, 2013; Stoodley, Harrison, & Stein, 2006; Stoodley, Ray, Jack, & Stein, 2008; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003) while others did not show group differences (Deroost et al., 2010; Hedenius et al., 2013; Kelly, Griffiths, & Frith, 2002; Rüsseler, Gerth, & Münte, 2006; van Witteloostuijn, Boersma, Wijnen, & Rispens, 2017). A meta-analysis of data from 14 studies that used SRT showed that children with DD have affected procedural learning (Lum, Ullman, & Conti-Ramsden, 2013). On the other hand, a meta-analysis that controlled for publication bias showed that the effect size may be zero between children with and without DD on implicit sequence learning (van Witteloostuijn et al.,

2017). Due to inconsistencies in findings it is hard to conclude anything from the existing results (Schmalz, Altoè, & Mulatti, 2017). One reason for the inconsistencies may be to do with the differences in the number of trials and complexities of sequences between studies (Lum, Ullman, et al., 2013). Another may be the greater researcher degrees of freedom the SRT paradigm allows in extracting the dependent variable for analysis (see Schmalz et al., 2018). Furthermore, it is timely that we go beyond initial learning and look at later learning phases in order to understand the true procedural capabilities in children with DD.

1.4. Procedural learning: Later phase

Memory traces created during initial learning undergoes offline sleep mediated consolidation. Consolidation is the process by which initially weak memories become strengthened and /or resistant to interference (Born, 2010). The process is also reported to take place within hours to days (that is, slow learning) (Doyon, Owen, Petrides, Sziklas, & Evans, 1996; Rångtell et al., 2017; Walker, 2003). To our knowledge, two studies have looked at the initial and later stages of procedural learning in DD, both yielding contrasting results. Gabay and her colleagues (Gabay et al., 2012) placed the consolidation stage after 14 hours of initial learning in both DD and typical readers. Findings showed that even though DD were poorer than typical readers on initial learning, their overnight performance improvement was similar to typical readers. Authors attribute their initial learning deficit to deficit in generalized skill learning component in DD. Hedenius and colleagues (Hedenius et al., 2013) compared three stages -initial online, progressive asymptotic and offline overnight after 24 hours, of skill acquisition using an alternating SRT (ASRT) task where the random trials are interleaved rather than blocked. Findings showed that DD were intact on the initial phase, however, their learning progress and consolidation were much lesser than typical readers.

1.5. The present study

The objective of the present study is to explore the initial and later learning stages of procedural memory in a group of good and poor readers in English, whose first language is Kannada. However, note that their English text exposure, as argued above, may be sufficient to master literacy skills in

English. We will examine their initial (on day 1) and later sequence (on day 2, at least > 24 hours and <48 hours after day 1) learning rates of 10-item first order visuospatial sequence using the SRT paradigm. The study also explores whether their procedural learning rates predict literacy scores in English. Given the diluted literature and lack of studies in this special population we do not have any confirmatory hypothesis. However, from procedural learning deficit theories we predict that the groups will differ in at least one learning session.

2. Method

2.1. Participants' details

Participants were recruited from Mysore district, Karnataka state, India. All the participants spoke Kannada as their first language; however, the medium of instruction as explained above is largely in English and exposure started from early age. Participants were tested as part of a Master student's dissertation at the All India Institute of Speech and Hearing (AIISH), Mysore. And, the procedure complied with the ethical guidelines for bio-behavioural research at AIISH. Parents were informed about the study and were given enough time to opt-out. The WHO 10 disability questionnaire (Singhi, Kumar, Malhi, & Kumar, 2007) ensured that none of the participants had any sensory, motor, and/or any notable developmental deficits (such as attention, language, and autism). No formal measure of L1 ability was taken; however, none of the participants were reported to have significant language delay in their oral L1 development. Note, the possibility of undetected language problem in L1 or L2 in our participants is not ruled out, which leaves the possibility that their literacy problem in English (based on which they are grouped) could be secondary to language problem, particularly in their L2 (Charles Alderson, Haapakangas, Huhta, Nieminen, & Ullakonoja, 2014). All the participants had standard score of 85 or above on Raven's Coloured Progressive Matrices (Raven, 2012) confirming that their non-verbal abilities were adequate.

There is no standardized literacy assessment tool for assessing reading abilities in Kannada children whose medium of instruction at school is English. Therefore, we administered the word reading and spelling subsection of the Dyslexia Assessment Profile for Indian Children (DAPIC) as a measure of

participant's literacy ability in English. On the word reading sub-test, they were given written form of 70 real words and asked to read them aloud one after another and the examiner noted the correctly read words (maximum score=70). On the spelling test the examiner read an item and its description (e.g., *The soldier carried a sword*, write *sword*) and the participant had to write the spelling of each item and the examiner noted the correctly spelled items (maximum score=40). This test is not standardized, hence could not be used here diagnostically. However, scores are available from a representative sample of 5 to 9 year olds on Kannada speaking English medium going children as part of unpublished master dissertation. A copy of the test material can be accessed here <https://osf.io/k6e2s/>.

Children grouped as poor readers confirmed to both the following criteria. First, based on parental/teacher report of reading and writing problems in classroom. That is, good readers had no complaints of reading/spelling difficulties in English and poor readers had complaints of reading and or spelling difficulties in English. We have little information about their reading in their L1. The relevance of testing reading abilities in Kannada may be argued in the present context as these children's exposure to Kannada scripts is limited (all but one subject of their curriculum is in Kannada). Second, based on the 'cut-off' scores for word reading or spelling, which is the reading and spelling mean score for age 9 in DAPIC (note all but 1 poor readers were over 9 years). That is, if a participant's score in both reading and spelling is 1.5 SD or more lower than the cut-off, they were grouped as poor readers. See Table 1 for summary of participants and pre-testing details (Appendix 1 for further details).

Insert Table 1 about here

2.2. Experimental Task and procedure

Procedural memory was measured using a version of SRT task (Nissen & Bullemer, 1987). On the SRT task, participants tracked the location of the stimulus (an illuminated circle) appearing in one of four horizontally aligned locations using spatially corresponding response keys on the keyboard ('Z',

‘X’, ‘N’, and ‘M’) as rapidly and accurately as possible. Participants were asked to use the left middle finger and index finger to respond for locations ‘Z’ and ‘X’ and right index and middle finger to respond for ‘N’ and ‘M’. At the beginning of each trial four asterisks appeared on the middle of the screen for 200 ms to prime the appearance of the stimulus, followed by the stimulus in one of the four locations until one of the designated key was pressed. The time gap between stimulus appearance and a key press was measured in milliseconds (see Figure 1 a). Unlike most SRT tasks, the present task was not self-paced. Incorrect responses provided a quick feedback message (written display of ‘*Oops!! wrong*’) on screen for 500 ms. Dependent variable was RTs for accurate responses. 15 practice trials proceeded to familiarize the participants with the task. The task consisted of five blocks; two random (R) and three pattern (P) (i.e., R1-P1-R2-P2-P3). On the random blocks (120 trials in each), the stimulus locations were random. On the pattern blocks, stimulus locations followed a pre-determined 12 item first order sequence, namely ‘421323413412’, in which all the locations have equal probability of occurrence (.25). Twelve items sequence set was repeated 20 times within each pattern block, therefore, each pattern block had 240 trials (see Figure 1 b).

2.3. Materials and sessions

The experimental tasks were designed using PsychoPy (Peirce, 2008), Builder version 1.83.00. The experiment was run on a laptop with screen size of 15.6 inches. Participants were visited thrice. On the first visit, the literacy and non-verbal IQ assessment was done. On the second visit, first 4 blocks (R1-P1-R2-P2) of SRT (called initial SRT) were administered. After at least 24 hours (but within 48 hours), they were revisited again and given the 5th block (P3), later SRT. And, the participants were not told about the sequences and the follow up SRT session. The timing of second session was not precisely recorded due to a programmer’s error.

Insert Figure 1 about here

3. Results

3.1. Data preparation

3.1.1. Dependent variable: Data processing and statistics were completed using R. First, RTs greater than 3000 milliseconds (ms) and less than 150 ms, were removed as it may be too slow or fast to be suggestive of underlying processes. On visualization, a clear speed accuracy trade-off was obvious (Appendix 2 a, b). Therefore, there was a need to combine the accuracy data with RT and extract a single RT measure. We followed the linear integrated speed-accuracy score (LISAS) procedure (Vandierendonck, 2017) to achieve this. As per this procedure, individual's RTs for a condition is increased, if the accuracy of that condition is compromised. Consider for an individual, the average correct RT of 500 ms with a standard deviation of 100 ms, and an error rate of .10 with a standard deviation of .05, LISAS will be $500 + 100/.05 \times .1 = 700$ ms. If the error rate is 0, the process is bypassed and the raw RTs remain unchanged. RTs corrected for inaccuracies was left skewed (see Appendix 3 a). Therefore, RTs were log10 transformed which resulted in near normal distribution (see Appendix 3 b). The log10 transformed RT is used as dependent variable in our statistical analysis. None of the participants could explicitly recall the complete 10 item sequence, however, some participants reported that they noticed patterns in some blocks.

3.1.2. Preparing the data for mixed models: Figure 2 shows speed of performance across blocks. On visualization, there is no learning slope on first pattern block. For ease of interpretation of the outputs of mixed models, the first pattern block was not included in the further analyses. The speeding up began from second pattern block (initial learning) and the learning slope is more obvious on third pattern block (later learning). Note the intercepts of the third pattern block dropped to the previous block and the drop is evident on both the groups. We have reasoned this effect in the discussion section. One of the reasons for using mixed models with the slope of learning across sets as random effects (see below) is to counter this effect. The main objective of the study is to check whether the groups differ on the learning slopes/rates on initial and later learning phases. To achieve that in two phased mixed models (see below), it is essential to have a reference slope (in this case, the random blocks) that is indicative of pure speeding up against which the learning slope for each learning phase

could be contrasted. Note, however, we did not have a reference block on day 2. Therefore, assuming that the slope of the random block will not vary between days we used the random block on day 1 as reference block on day 2 as well. That is, we prepared two data frames, one with default random blocks (1 and 2 combined, thus 240 trials) on day 1 along with initial learning block (pattern block 3, thus 240 pattern trials). The random blocks were appended from day 1 to day 2 data frame as well along with later learning trials (pattern block 3, thus 240 trials) (see Figure 1 c). For ease of visualization, trials were grouped into sets (1 set = 20 trials), and a median RT per participant per set is taken (Figure 2's y-axis is the group mean of this median RT). The two data frames used in the mixed models are accessible here <https://osf.io/j8wkd/> (day 1 data frame) and here <https://osf.io/gjhza/> (day 2 data frame).

Insert Figure 2 about here.

3.2. Statistical analysis

3.2.1. Initial versus later learning rates: We set up two identical models to examine the phase and group slope interaction on each day separately. The basic idea is to compare model two phases (reference versus learning) of data with a cut-off point at which a change has occurred, leading to the expectation that the regression of score on time will change. To achieve this we used a regression discontinuity model (Moscoe, Bor, & Bärnighausen, 2015), which was adapted by Kuppuraj et al. for quantifying learning (Kuppuraj, Duta, Thompson, & Bishop, 2018). A linear mixed effects model that includes fixed effects for phase (learning and random/reference), group (good and poor readers), slope across the phases and the interaction between them was constructed using *lmer* function of *lme4* package (Bates, Mächler, Bolker, & Walker, 2015). The baseline condition for group is poor readers and the baseline condition for phase is reference/random sequence. Thus, the interaction term indexes the mean difference in RT across groups and phases. And, this interaction is of interest in the present study.

The slope of learning across sets was treated as a random effect. There were 24 sets in total (12 random and 12 pattern). Because of the two-phase design (regression discontinuity), we re-specified the set index variable into two variables, ‘b1’ and ‘b2’, for phase 1 (learning phase) and phase 2 (break phase), respectively. This allows for the correct estimation of regression line for each phase under one estimation process. The set index was centred at zero, therefore, the point of discontinuity is zero. That is, b1 had negative indexes until the discontinuity for the learning phase, but then fixed zero values after the discontinuity in the random phase. For the reference phase, b2 variable was coded as zero prior to discontinuity and positive set values in the reference phase, as is typical in regression discontinuity design. The analysis was run on initial and later data sets separately. The output of the model is shown in table 2. The effects that are important for addressing the present question is shown in bold. It shows that on initial learning output, the learning slope was significant than reference slope ($t = -3.88^{***}$), and the groups did not differ on the learning rate indicated by absence of group and phase interaction ($t = .9$) (see Appendix 4 a). On day 2, the learning slope was lot better than reference slope ($t = -10.48^{***}$), and the group and phase interaction also reached significance ($t = -5.98^{***}$). This suggests that good readers showed significantly higher learning rate compared to poor readers on later learning phase (see Appendix 4 b). A third model was run, with initial and later learning phases only. This showed that the later learning slope was significantly more than initial learning slope ($t = -7.87^{***}$) and the later slope was particularly higher in good readers ($t = -6.31^{***}$) (see Appendix 4 c). An .rmd file that analyses the raw data and fits the model can be accessed here <https://osf.io/ynaqw/>.

Insert Table 2 about here

3.2.2. Correlation: We used *sens.slope* function in R to extract slope of each individual for initial and later learning phases. This function gives an estimate of slope. A negative estimate value indicates downward slope (learning) and values of less than or equal to zero indicates absence of learning. We used the slope estimate value as a measure of individual differences in learning rates and correlated them to reading and spelling raw scores. The findings showed no correlation between any of literacy and procedural learning slopes in good [word reading with initial learning slope= -0.24, word reading

with later learning slope= 0.39, spelling with initial learning slope= -0.04, spelling with initial learning slope= 0.03] or in poor readers [word reading with initial learning slope= -0.05, word reading with later learning slope= 0.01, spelling with initial learning slope= -0.12, spelling with initial learning slope= 0.02]. Note, for $n = 22$, correlation of $\geq .43$ is significant at α of .05. The internal consistency of the learning trails were very high in the present task (good readers =.92, poor readers = .90 and all together = 0.91).

4. Discussion

Adequate initial sequence learning in poor and good readers of English in the present study is consistent with earlier studies that looked at only initial phase of procedural learning in children with DD (Deroost et al., 2010; Hedenius et al., 2013; Kelly et al., 2002; Rüsseler et al., 2006; van Witteloostuijn et al., 2017). The finding is in contradiction to studies that found affected initial learning in children with DD (Gabay et al., 2012; Howard et al., 2006; Jiménez-Fernández et al., 2011; Lum, Conti-Ramsden, et al., 2013; Stoodley et al., 2006, 2008; Vicari et al., 2003). A surprising drop in intercept on day 2, might be due to release from reactive inhibition (Leeper & Hull, 1952). Reactive inhibition is the tendency for the response magnitude to drop after repeated exposure to same stimulus. It may be the case that our participants' responses were inhibited towards the end of day 1 and the rest has released the inhibition, therefore, allowing them to start responding at a dropped intercept level (Sengottuvel & Rao, 2013a). Present results, as a whole, are comparable to Gabay et al's and Hedenius et al's (Gabay et al., 2012; Hedenius et al., 2013). The present findings showing intact initial and affected later learning in poor readers are in line with Hedenius et al's and in contrary to Gabay et al's who found the opposite.

What might have caused the difference with Gabay et al's ? Affected initial learning in some studies may indicate a purely reaction time based learning deficit (Ferraro et al., 1993; Knopman & Nissen, 1991). That is, it may be the reflection of participant's slowness in forming the stimulus to response key mapping in general and not a deficit in encoding of sequence-specific information as such. Note, our regression discontinuity approach allows to detect the difference in slope between learning and reference/random slope, therefore, shows sequence -specific learning effects (happens in learning

phase) independent of general motor speeding up (happens in reference/random phase). Note, Gabay and colleagues have also proposed this as one of the reasons for poor initial learning in their DD participants.

What caused the group differences in later learning? This is a crucial finding of the present study. It is worth noting that the structural aspects of procedural memory, spreads across Broca's area in frontal and striatum in basal-ganglia and cerebellum (Ullman, 2001a). It is shown that certain structures such as striatum (in basal ganglia) is continued to be active throughout later learning stage of procedural memory (Doyon et al., 1996; Exner, 2002; Lehericy et al., 2005). It may be the case that our poor readers' procedural deficits are contained to circuits within procedural system which plays crucial role in procedural learning beyond the fast acquisition stage (such as striatum). It is hard to hypothesize that the group differences on later learning phase may have been caused by our group characteristics as there was no relation between memory and literacy scores. The results might be interpreted with caution as our poor readers' learning rate on day 2 may be confounded with their poor sleeping nature (Richdale & Baker, 2014; Tietze et al., 2012). It is well known that sleep plays significant role in offline- memory consolidation (Backhaus, Hoeckesfeld, Born, Hohagen, & Junghanns, 2008; Dumay & Gareth Gaskell, 2005; Potkin & Bunney, 2012; Rasch & Born, 2013). And, children with developmental disorders in particular do not benefit from sleep as well as typical children (Carotenuto, Esposito, Cortese, Laino, & Verrotti, 2016; Mercier, Pivik, & Busby, 1993; Smith et al., 2017). Therefore, it is not clear whether the present group differences on day 2 are indicative of their learning differences or confounded with poor readers' sleeping characteristics and sleep related consolidation deficits.

Implying from the unique population. Present findings show no correlation between procedural and literacy scores. Lack of correlation between procedural and literacy measures were also reported in the past (Schmalz et al., 2018; Waber et al., 2003). The lack of correlation between procedural memory with literacy in English (L2 for our participants) may be due to following reasons. First is related to the task parameters, reliability of the SRT tasks. For correlations to be detected, the tasks must be sensitive to individual differences in learning (historically a test retest correlation of $\geq .6$).

However, reliability of SRT tasks have been criticized (Siegelman, Bogaerts, Kronenfeld, & Frost, 2017; West, Vadillo, Shanks, & Hulme, 2018). Our task, therefore, runs the risk of being unsuitable to be used in correlational approaches (Hedge, Powell, & Sumner, 2017). Second, is related to the underlying process. That is, a memory system other than procedural may underlie learning of literacy in our population. It has been argued that L2 learning may depend on individual's declarative capacity, at least in initial stages (Brill, Faretta, Wong, Wong, & Morgan-Short, 2011; David W. Green & Green, 2010; Ferman & Karni, 2011; Sagarra, 2010; Ullman, 2001b; Ullman & Lovelett, 2016). This argument maintains that until the acquired skill (here literacy) is fully automatic, it may not be transferred to the procedural system. On this very sample, it has been shown that declarative gain (difference between later and initial learning via declarative system) predicted good readers' English literacy (Kuppuraj et al. in preparation). Further, a more prominent and immediate storage capacities, such as working memory may underlie reading (Chiappe, Siegel, & Hasher, 2000; Gathercole, Alloway, Willis, & Adams, 2006; Nouwens, Groen, & Verhoeven, 2017).

Limitations and future directions: The present study, has several limitations which the future studies may address. First, a detailed language and literacy (L1 and L2) profiling would have given more conclusive findings. Second, a default random block on day 2 would have given more realistic estimate of motor speed on day 2. Third, as mentioned above, it is not known whether the lack of correlation in the present study implies underlying relationship or just a failure to detect it. Fourth, the time gap between the sessions was not strictly maintained nor was it recorded. This may have affected the performance on day 2. At least four research questions are ripe from the present findings. First, if it is not the procedural memory, then what predicts their literacy in our special population? One alternative is their declarative memory. Second, is to extend the present study to examine whether the groups differ on the asymptotic characteristic of the learning curve. We propose that poor readers may reach the asymptote level similar to typical readers but take more trials to achieve it. Third, is to develop tools that goes beyond detecting group differences and be able to detect individual differences. Such step is crucial for correlational studies (Kuppuraj et al., 2018; Schmalz et al., 2018). Fourth, the existing theories predicting procedural deficits in poor readers, are not equipped to

accommodate the findings showing differences between learning phases in good and poor readers. One crucial step forward is to propose revisions to such theories, to better accommodate empirical data.

5. Conclusion

The present study examines the initial and later sequence learning phases, in a group of children with and without reading difficulties in English. The population is unique in the sense that English is not their L1.. And, despite poor oral proficiency in English they get great exposure to English texts in schools from very early in life. This is the first data set on procedural memory in Indian children with reading difficulties. We found that poor readers of English were comparable to good readers on initial learning only, but their later learning slope was significantly poorer than good readers. We also found that the learning slopes did not predict their English reading or spelling scores in English. The findings suggests that to get holistic picture on poor readers' learning difficulties, their learning abilities beyond initial learning must be documented in future studies. Though, findings are in support of theories claiming procedural deficits in DD (R. I. Nicolson et al., 2010; Roderick I. Nicolson & Fawcett, 2007, 2008; Ullman, 2016), they also urge the theories to be more accommodating of group differences across learning phases.

Open materials and data: The tasks used and all the raw data files can be accessed here

<https://osf.io/asqzp/>.

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Conflict of interest statement

Authors declare no conflict of interest related to this work

Author contributions

KS: Conceived the idea, analysed the data, performed statistical analysis, wrote the paper, and reviewed the manuscript. AV: Lead the second half of the study from India, collected data, organized the data, and reviewed the manuscript.

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a

b

c

Model 1 data set: Comparing slope of initial with reference phase

1st Random, 2nd Random = Reference phase (240 trials)

2nd Pattern = Learning phase (240 trials)

Model 2 data set: Comparing slope of later with reference phase

1st Random, 2nd Random = Reference phase (240 trials)

3rd Pattern = Learning phase (240 trials)

SRT_error

SRT_speed

Interaction effect of Group and phase on DV

Interaction effect of Group and phase on DV

Interaction effect of Group and phase on DV

Table1. Pre-testing and comparisons																
	Age				Non-verbal IQ				Word Reading				Spelling			
Group	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Good readers	12.23	1.27	10	14	107.55	6.12	100	119	56.23	5.12	49	67	30.09	3.05	26	39
Poor Readers	11.64	1.89	7	16	101.05	10.66	88	125	13.77	6.1	3	29	8.95	4.25	2	19
Difference	t=1.22				t=2.48*				t=25.00**				t=18.95**			

Table 2. Out of all three mixed models

Fixed effects	Random versus initial learning						Random versus later learning					
	Estimate	CI(lower)	CI(upper)	Std.Err	t	p	Estimate	CI(lower)	CI(upper)	Std.Err	t	p
<i>Group</i>												
TD	-0.015	-0.038	0.009	0.012	-1.230		-0.015	-0.038	0.008	0.012	-1.260	
<i>Phase (baseline =reference)</i>												
Learning	-0.046	-0.070	-0.023	0.012	-3.880	<.001	-0.122	-0.145	-0.100	0.012	-10.480	<.001
<i>Set</i>												
Learning	0.001	-0.004	0.006	0.003	0.370		0.001	-0.004	0.006	0.003	0.370	
Random	0.001	-0.005	0.006	0.003	0.310		0.001	-0.005	0.006	0.003	0.190	
<i>Interactions (baseline group = PR)</i>												
Group(TD) X Phase(Learning)	0.015	-0.018	0.048	0.017	0.900		-0.099	-0.131	-0.066	0.017	-5.980	<.001
Group(TD) X set (Learning)	-0.002	-0.010	0.005	0.004	-0.610		-0.002	-0.010	0.005	0.004	-0.610	
Group(TD) X set (Random)	-0.001	-0.009	0.007	0.004	-0.300		-0.003	-0.012	0.005	0.004	-0.810	
<i>Random effects</i>												
	Variance	SD	Correlation				Variance	SD	Correlation			
ID:Group on b1	0.000	0.011					0.000	0.011				
ID:Group on b2	0.000	0.012	0.950				0.000	0.013	0.680			
Residuals	0.004	0.065					0.004	0.063				

		Initial versus later learning				
Fixed effects		CI(lower)	CI(upper)	Std.Err	t	p
<i>Group</i>						
TD	-0.015	-0.037	0.022	0.011	-1.360	
<i>Phase (baseline = initial)</i>						
Later	-0.087	-0.109	0.022	0.011	-7.870	<.001
<i>Set</i>						
Learning	-0.001	-0.006	0.005	0.003	-0.310	
Random	0.001	-0.005	0.006	0.003	0.190	
<i>Interactions</i>						
Group(TD) X	-0.099	-0.129	0.030	0.016	-6.310	<.001
Phase(Later)						
Group(TD) X set (initial)	0.001	-0.006	0.008	0.004	0.310	
Group(TD) X set (later)	-0.003	-0.012	0.008	0.004	-0.820	

Variance	SD	Correlation
0.000	0.012	
0.000	0.013	0.600
0.004	0.060	

Appendix 1. Details of participants. Group 2 is Poor readers, Group 1 is Good readers, WR_70 is score on word reading out of 70 English words, SP_40 is score on spelling out of 40 English words.

Grade	Age	Group	Gender	IQ	WR_70	SP_40	1.25 SD lower limit (WR)	1.25 SD lower limit (SP)
>V	10	2	1	110	14	12	48.72	25.3
>V	13	2	2	97	16	13	48.72	25.3
>V	11	2	1	103	22	13	48.72	25.3
>V	13	2	1	100	11	10	48.72	25.3
>V	14	2	1	110	13	10	48.72	25.3
>V	11	2	1	103	17	12	48.72	25.3
>V	10	2	1	107	18	9	48.72	25.3
>V	10	2	2	110	12	7	48.72	25.3
>V	12	2	1	107	14	11	48.72	25.3
>V	12	2	2	90	15	7	48.72	25.3
>V	13	2	1	93	13	5	48.72	25.3
>V	10	2	1	100	7	4	48.72	25.3
>V	12	2	1	93	14	8	48.72	25.3
>V	13	2	1	107	16	8	48.72	25.3
>V	10	2	1	88	24	19	48.72	25.3
>V	13	2	2	88	6	4	48.72	25.3
>V	16	2	2	115	29	17	48.72	25.3
>V	11	2	1	125	8	6	48.72	25.3
>V	10	2	1	88	7	9	48.72	25.3
>V	12	2	1	88	3	2	48.72	25.3
III	7	2	1	113	15	6	21.62	20.2
>V	13	2	1	88	9	5	48.72	25.3
>V	13	1	2	110	49	27	48.72	25.3
>V	14	1	2	115	67	31	48.72	25.3
>V	13	1	1	107	59	30	48.72	25.3

>V	14	1	1	100	60	32	48.72	25.3
>V	14	1	1	107	51	29	48.72	25.3
>V	14	1	2	107	56	39	48.72	25.3
>V	11	1	1	119	49	26	48.72	25.3
>V	13	1	1	115	56	28	48.72	25.3
>V	12	1	2	100	54	27	48.72	25.3
>V	13	1	2	107	55	29	48.72	25.3
>V	12	1	1	107	56	28	48.72	25.3
>V	11	1	2	115	53	29	48.72	25.3
>V	11	1	1	115	58	28	48.72	25.3
>V	12	1	1	110	50	30	48.72	25.3
>V	12	1	2	103	54	27	48.72	25.3
>V	12	1	2	100	50	29	48.72	25.3
>V	13	1	2	100	58	32	48.72	25.3
>V	13	1	1	107	63	36	48.72	25.3
>V	11	1	1	107	62	31	48.72	25.3
>V	10	1	2	100	53	31	48.72	25.3
>V	11	1	2	100	59	30	48.72	25.3
>V	10	1	1	115	65	33	48.72	25.3

Figures in text captions

Figure 1. a) Serial reaction time task: A prime appears for 200ms followed by stimulus (yellow) in one of the locations until a spatially corresponding button is pressed. In this example, 'z' is the correct response on trial one and 'n' is correct response on trial 2. Note any response using the designated keys ends the trial. Both accuracy and RT were measured, b) Shows the design, c) schematics of data sets used in mixed model.

Figure 2. Displaying the SRT data

Figures in Appendix captions

Appendix 2. Normality check

- a. Raw RT distribution, b. Log10 RT distribution

Appendix 3. Speed accuracy trade-off

- a. Inversed RT across blocks , b. Proportion error per block

Appendix 4. Interaction plots from lmer

- a. Initial vs. Reference data, b. Later learning vs. Reference data, c. All learning data