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Neurophysiological Measures and Developmental Dyslexia: Auditory Segregation Analysis

Introduction

- 1 Current theories of dyslexia emphasise difficulties in auditory phonological processing and/or in processing rapid temporal stimuli, such as speech stimuli (for a review see Habib (2000) and other papers in this issue for discussions). Speech processing can be viewed as complex acoustic-processing task in which incoming acoustic input is sorted into one or several distinct perceptual objects according to Gestalt principles (i.e., auditory scene analysis). An important aspect of auditory scene analysis that has received little attention is the segregation of concurrent auditory events, i.e., distinguishing separate sound objects on the basis of stimulus features, such as localisation or frequency. Previous research has shown that school-aged children have more difficulty than adults in identifying words embedded in a background of multi-talker babble. Fallon et al. (2000) suggested that these age-related differences were related to the ability to perceptually segregate acoustic elements that belong to the target word from those that belong to the babble. From this perspective, studying auditory segregation abilities in dyslexic and non-dyslexic children may help determine if difficulties in this perceptual processing contribute to the auditory dysfunction reported in dyslexia.
- 2 The present study used behavioural and electrophysiological, event-related potential (ERP) methods, as ERPs are a powerful means of studying temporal and spatial aspects of cognitive processes in the brain, and can be used to examine the levels of processing involved in cognitive and perceptual tasks in normal and clinical populations. Many studies have now investigated the neurophysiological correlates of dyslexia in children in attempts to identify the cognitive dysfunction(s) that produce the reading disability, with recent studies using reading (i.e., visual) or auditory tasks, and are reviewed briefly below.
- 3 Taylor and Keenan (1990) studied dyslexic children with visual processing impairments using three reading-related tasks and found delayed N2 and P3 components in the dyslexics, but normal maturational changes. A later study (Taylor & Keenan, 1999) included a phonological task, with orthographic and semantic tasks, assessing dyslexic children with auditory processing impairments. Latency differences between dyslexics and controls were most marked on the phonological task. Both of these studies found the ERP distributions to differ between the dyslexics and controls, consistent with a different cortical utilisation in the dyslexic children. Khan et al. (1999) found significant group effects in the early components, P2 and N2, with reading tasks between control children and children at risk for reading difficulties. The latter showed less asymmetry in these components (250-400ms) associated with stimulus evaluation and pre-lexical processing than did the non-dyslexics, further suggesting the use of different strategies. With various silent reading tasks Georgiewa et al (1999) found left frontal asymmetries between dyslexics and control children using fMRI, and concluded that this demonstrated impaired phonological processing. In a later study that also included ERPs, they confirmed this asymmetry and further noted that it occurred in the 250-600ms time window (Georgiewa et al. 2002). Shaywitz et al. (2002) used four reading-related tasks with a large series of dyslexic children and also found consistently lower activation in left hemisphere sites in fMRI measures. In the older dyslexic children, however,

there was also activation of right frontal sites with the more difficult tasks, and this they suggested reflected compensatory mechanisms. During a pseudo-word rhyming task Simos et al. (2000) showed greater right hemisphere activation after 300ms in 12-17 year-old dyslexics.

A shift to left hemisphere activation was seen in dyslexic children following remediation (Simos et al. 2000). These studies suggest that the typical left-hemisphere dominance for reading tasks is not present in dyslexia, although it can emerge with training.

4 Recent neurophysiological studies in dyslexia with auditory stimuli have examined the mismatch negativity (MMN), a difference component elicited by any discriminable physical change in a repetitive auditory stimulus, regardless of attention to the stimuli (Kujala & Näätänen, 2001). In several studies researchers have found that only some types of stimuli (such as speech stimuli or pitch changes) produce smaller MMN amplitudes in dyslexic compared to control groups (Schulte-Körne et al., 1998; Baldeweg et al., 1999). The MMN can also reflect functional changes in auditory processing, and thus has been applied to the assessment of training effects in dyslexia (see Kujala & Näätänen, 2001, for a review). As an increase in MMN amplitude reflects ease of detecting differences, these studies demonstrate that for specific types of sounds the differences among stimuli were less perceptible for dyslexic subjects. Baldeweg et al. (1999) suggested that an impairment in frequency analysis in dyslexia may lead to distorted phonological representations, and thus the phonological deficits.

5 In the present study we wished to evaluate the processing of complex sounds – concurrent auditory processing - in dyslexic children, as segregating incoming auditory stimuli into discriminable parts is a critical aspect of phonological and speech processing in the natural environment. Only a few studies have investigated this behaviourally (Sutter et al., 2000; Helenius et al., 1999), and have found impairment in auditory segregation in dyslexic adults.

Sutter et al (2000) found that dyslexics have deficits in the perception of frequencies of auditory stimuli, in higher order or global abilities to group auditory objects. When frequency was not manipulated, but only the timing (Helenius et al., 1999), dyslexic adults showed stream segregation at longer stimulus onset asynchronies (SOA) than control subjects, suggesting that they could not process the very rapid stimulus presentations. Auditory stream segregation gives the impression of two simultaneous trains of stimuli, depending on the temporal (SOA) separation. Here, we used simultaneously presented sounds that subjects should be able to perceive as separate concurrent sounds, depending on the frequency separation. The stimuli were loudness-matched complex sounds that had either all tuned harmonics, or one mistuned harmonic that if mistuned by more than 4% subjects hear as an additional tone (Alain, Arnott, & Picton, 2001). The perception of concurrent auditory objects is associated with an enhanced negativity peaking at about 180ms, referred to as the object-related negativity (ORN). This component is distinct from the MMN, which reflects a mismatch between a rare incoming auditory stimulus and very frequent repetitive stimuli, whereas the ORN indexes an “online” detection of simultaneous auditory objects. We hypothesised that dyslexic children would have greater difficulty in perceiving the two concurrent auditory objects, that the ERPs would reflect the perception of one or two distinct sounds, and that there would be group differences in both behavioural and neurophysiological measures of concurrent sound segregation.

Method

Participants

6 Twenty-two 8-12yr-old children participated in the experiment, 11 dyslexic children (mean = 10.08 ± 1.3yrs) and 11 non-dyslexic children (10.29 ± 1.2yrs). All children had French as their mother tongue, and none had a history of hyperactivity or neurological disorders. The dyslexic children fulfilled the following inclusion criteria: at least an 18-month delay in their reading level and below normal scores on the ‘L2MA’ battery (Chevrie-Muller, 1997) which includes

tests of phonetic fluency, repetition of difficult words, reading irregular words, reading and writing of pseudo-words (see Table 1). None of the dyslexic children had a general IQ (from the WISC III) below 90, visual or auditory dysfunction, dysphasia or compensated dyslexia. The non-dyslexic children had no reported evidence of difficulties at school, no interventions with speech therapists, all successfully completed the reading test 'Alouette' and scored at least 13/15 on dictated pseudo-words. None of the children had colds or ear infections at the time of the study. All participants provided informed consent; informed written consent to participate in the study was also obtained from their parents.

Table 1. Summary of reading level performance of the dyslexic children in the study, including the results of on the L2MA battery (Chevie-Muller, 1997).

Chronological age (years)	Reading irregular words		Reading pseudo-words	
	Performance (/20)	Reaction time (ms)	Performance (/20)	Reaction time (ms)
10.29 ± 1.2yrs	7.82 ± 3.22	1753.36 ± 963.94	10 ± 2.49	1626.14 ± 774.29
Delay in reading (months)	Phonological awareness		Phonemic awareness	
	Performance (%)	Reaction time (s)	Performance (%)	Reaction time (s)
35 ± 15.17	78.18 ± 21.82	51.45 ± 17.39	64.36 ± 27.02	62 ± 23.85

Stimuli and Task

- 8 The stimuli consisted of five complex sounds that were obtained by combining 12 pure tones with equal intensity. All five stimuli had a 400-ms duration including 10 ms rise and fall time and a fundamental frequency of 200 Hz. Stimuli were presented binaurally through Firstline H1096 headphones at 70dB SPL. For four of the stimuli the frequency of the 3rd harmonic varied; it was shifted upward by 2, 4, 8 or 16% of its original value (i.e., the 600 Hz 3rd harmonic was replaced with 612, 624, 648, 696 Hz tones). Within each block of trials, the five different stimuli (one harmonic and four inharmonic stimuli) were presented ten times each in random order.
- 9 The task for the participants was to indicate on each trial, by pressing the number "1" or "2" on the number pad of the keyboard with their dominant hand, whether they heard a single complex sound with one pitch or whether they heard two sounds, one buzz plus another sound with a pure tone quality. Following the response, there was a 1000ms lag before the next sound was presented. Participants were given a series of practice trials to familiarize them with the task with feedback provided, but received no feedback on their performance during ERP recording. The five blocks of 50 trials each were then presented, with a brief pause between blocks.

ERP Recording

- 10 EEG was recorded from 32 electrodes in an EasyCap according to the 10-10 system. The electrodes were referenced to Cz and an averaged reference computed off-line. EOG was monitored from 3 electrodes, at the outer canthi and the supraorbital ridge of the right eye. Data were recorded continuously using a Neuroscan 4.0 system with a sampling rate of 500 Hz, a bandpass of 0.1-30Hz, a gain of 500; electrode impedances were below 5K Ω . Data were epoched off-line into 1.1s intervals with a 100ms pre-stimulus baseline, baseline corrected and those trials with artefacts were rejected at $\pm 90\mu\text{V}$. The data were sorted and averaged by group and stimulus.

Data Analysis

- 11 For each child, the peaks were measured on their averaged ERPs for each stimulus separately. The peaks of interest for early auditory processing were the N1a, b and c components

(Näätänen & Picton, 1987; Bruneau et al., 1997; Pang & Taylor, 2000), the ORN and the later positive component P400 (Alain et al., 2001; 2003). Peaks were measured at the electrode sites where the peak was maximal (Picton et al., 2000): the vertex N1b was measured at fronto-central (F3, Fz, F4, C3, Cz, C4), the temporal N1a at fronto-temporal and temporal (FT7, FT8, T7, T8), the N1c at temporal (T7, T8) and ORN and P400 at midline fronto-central (Fz, Cz) sites. The ORN was obtained by subtracting the tuned (0%) from the mistuned by 16% stimuli, and the mean amplitude between 140-240ms was measured. The P400 was measured as the mean amplitude between 300-400ms.

- 12 Data were analysed with repeated-measures ANOVAs, with adjusted degrees of freedom, using the variables of group and sound, and significant effects were examined with Bonferroni post-hoc analyses. The latencies and amplitudes of the various components were analysed for three stimulus categories (0%, 4% and 16% mistuning) but the effects with mistuning were gradual (see figure 2a); thus the final analyses compared only the extremes of the continuum: 0% (i.e. tuned) versus 16% (the most mistuned) stimuli (fig. 2a). Behavioural data (accuracy and reaction times) were also submitted to repeated-measures ANOVAs.

Results

- 13 Behavioural. Accuracy for correct identification of the mistuning varied considerably with the stimuli; all of the children had the greatest difficulty with the mistuning of 2% and the sound with the 16% mistuning was the easiest ($F(1.6,32.2) = 23.1, p < .0001$). There was a small effect of group ($F(1,20) = 4.5, p < .047$), as the dyslexic children were less accurate than the controls (fig. 1). The dyslexic group had longer RTs than non-dyslexics ($F(1,20) = 5.9, p < .025$) (fig. 1) and reaction times (RTs) were faster for the sounds with the greatest mistuning ($F(1.9,37.4) = 5.1, p < .001$).

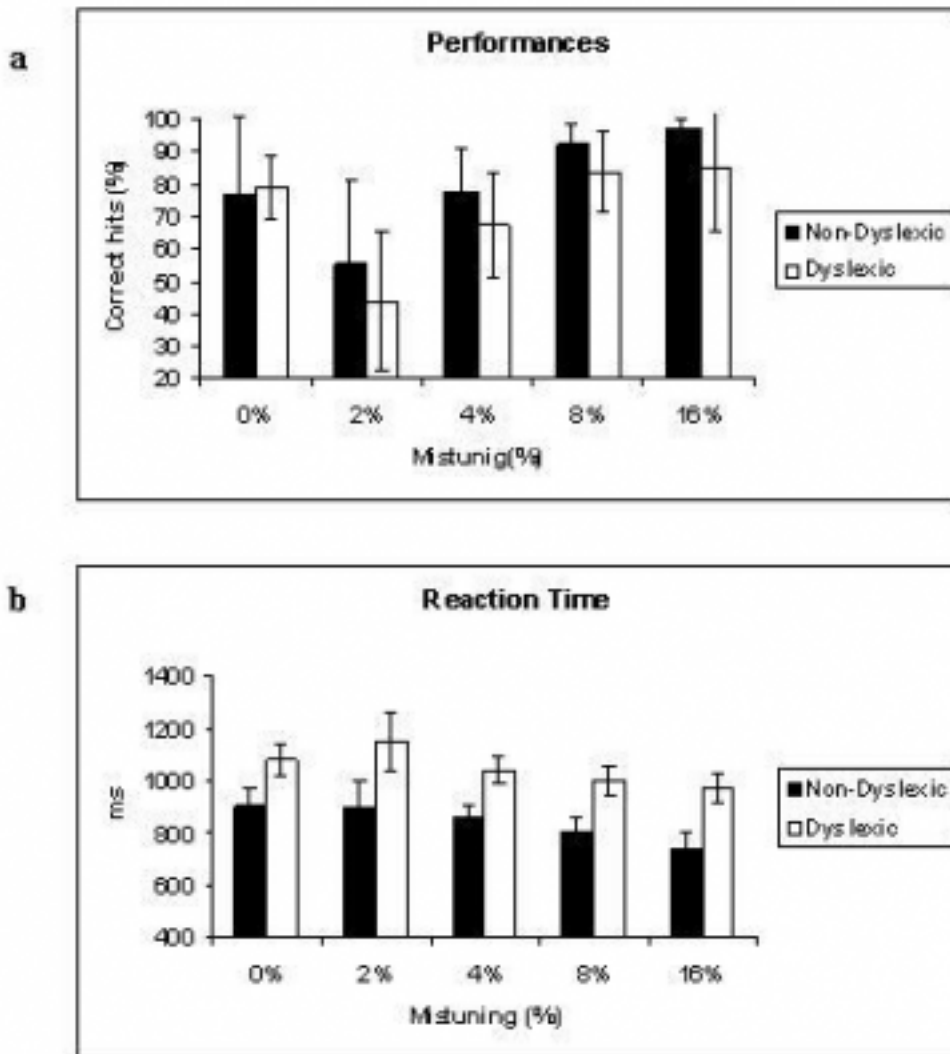


Figure 1. Mean accuracy (a) and reaction times (b) for the dyslexic and non-dyslexic children for the five auditory stimuli used (tuned, 0%, and mistuned at 2%, 4%, 8% and 16%).

- 14 Neurophysiological. N1a latency (mean 103ms) was longer for tuned (16%) than the mistuned stimuli ($F(1,20) = 6.6, p < .019$). N1a amplitude showed significant effects of group ($F(1,20) = 6.7, p < .018$) due to larger amplitudes seen in the dyslexic children at fronto-temporal sites. However, this interacted with sound; the dyslexic children had larger amplitudes for the tuned stimuli, whereas the control children had larger amplitudes for the mistuned stimuli ($F(1,20) = 6.2, p < .02$).
- 15 The second temporal auditory component, N1c (mean latency 207ms) was slightly shorter for the tuned than mistuned stimuli ($F(1,20) = 4.6, p < .044$) and as this interacted with electrode ($F(1,20) = 5.6, p < .029$), the electrodes were analysed separately. These analyses showed a shorter N1c latency for the tuned stimuli ($F(1,20) = 6.8, p < .017$) and N1c was also shorter for the dyslexic than control children ($F(1,20) = 5.5, p < .029$), but only over the right lateral temporal electrode. N1c amplitude was larger for mistuned than tuned stimuli ($F(1,20) = 5.9, p < .025$), with no group effects or interactions (fig. 2a).

Figure 2. a) Grand averaged ERPs for the dyslexic children showing, from the left temporal electrode (T7), the N1a-N1c complex and at the vertex (Cz electrode) the N1b, over-plotted for three of the stimuli (0%, 4%, 16%). b) Mean ERP amplitudes for the three N1 components to the tuned (left panel) and mistuned by 16% (right panel) for the dyslexic and non-dyslexic children. c) Grand averaged ORN over-plotted for the dyslexic and non-dyslexic children, from the midline electrodes (Fz, Cz) showing the larger amplitude (more negative) for the dyslexic children

- 16 The positive peak between the N1a and N1c, referred to here as P1a (mean 159ms), was also measured at temporal sites, to obtain further precision on when the group differences in early auditory processing first appeared. The P1a latency was shorter for tuned (154.6ms) than mistuned (164.5ms) sounds ($F(1,20) = 7.7, p < .011$) and shorter for the dyslexic (152.8ms) than control (166.3ms) children ($F(1,20) = 5.1, p < .035$). Thus the group latency differences started between the N1a and N1c, being present at the P1a latency. P1a amplitude was larger for the mistuned stimuli ($F(1,20) = 23.2, p < .0001$) and larger over the right than left anterior temporal sites ($F(1,20) = 10.5, p < .004$).
- 17 The most frequently recorded auditory ERPs, the vertex N1b (165ms) showed only amplitude effects of the stimuli ($F(1,20) = 7.4, p < .013$) (fig. b) and electrode ($F(3.1, 61.1) = 24.8, p < .0001$) due to larger amplitudes to the mistuned stimuli, and larger amplitudes over frontal than central sites, consistent with the developmental literature (Pang & Taylor, 2000).
- 18 The ORN which reflects the processing of auditory objects, obtained by subtracting the tuned from the 16% mistuned stimuli (Alain et al., 2001), was larger for the dyslexic children ($F(1,20) = 4.5, p < .047$; fig. 2c). The ORN latency (180ms) did not differ between the two groups of children. No group effects were seen for P400; thus, processing differences in auditory segregation analysis between dyslexic and control children were seen only at earlier processing stages.

Discussion

- 19 The mistuning of the stimuli had the expected effects behaviourally and produced distinct pattern of effects in the resultant ERPs. The dyslexic children had lower performance levels on the task, but the differences were less than expected given the literature (e.g., Helenius et al, 1999). However, the reported studies used stream segregation, which requires rapid temporal auditory processing rather than the auditory segregation of the present task. The auditory streaming paradigm may be more difficult for dyslexics; future studies will verify this. The reaction times though, were longer in the dyslexic than non-dyslexic children, suggesting that the former required more time to decide that the stimuli were either one or two sounds, consistent with the suggestion of Sutter et al (2000) that dyslexics have difficulties in grouping auditory objects. Serniclaes et al. (2001) suggested that dyslexics may have trouble in the construction of phonemic categories, which could be related to the difficulty seen here with auditory grouping or scene analysis.
- 20 The differences in the various stages of auditory processing differed between the dyslexic and non-dyslexic children, as seen in the auditory ERPs. Amplitude effects were seen in the earliest peak measured, N1a, which showed greater negativity for the dyslexic children. Larger amplitudes across groups were seen for mistuned stimuli, for P1a, N1b and N1c (150-210ms), suggesting greater processing requirements for the stimuli that contained effectively two sounds. Comparably, the larger amplitudes seen in the dyslexics for the N1a, which reflects early perceptual processing (Pang & Taylor, 2000 Näätänen & Picton, 1987), suggests that they required greater activation for this stage than the control children. Helenius et al (2002) also found increased early negativities over left temporal regions to speech sounds in dyslexics. The ORN effectively reflects the processing of the second sound, as it is a difference between the tuned and the mistuned sounds – the latter producing the perception of two sounds. For the ORN the dyslexic children also had greater negativity (fig. 2c), arguing that for the discrimination of two versus one auditory objects greater cortical activity is required, which fits with their poorer performance and longer RTs. ORN decreases with age (Alain et al., 2003), so the larger response in the dyslexics could also reflect a more immature processing. This is in contrast to MMN results, where dyslexic subjects had smaller responses to frequency discriminations (Baldeweg et al., 1999), underlining the fact that in both cases, frequency

processing appears impaired, but that the two ERP subtraction measures (MMN and ORN) do index differing aspects of auditory perception.

- 21 P1a and N1c latencies were longer for the mistuned than tuned stimuli, probably due to the mistuned stimuli requiring slightly longer time for the segregation of the two sounds to occur. These same two components also showed group differences. The fact that P1a was longer for the control than dyslexic children, we interpret to be due to the dyslexic children processing the two sounds superficially. This effect was also seen at the right temporal sites for N1c, perhaps due to this processing occurring preferentially in the right hemisphere, consistent with various neuroimaging studies that have reported relatively greater right than left hemisphere activation in dyslexia (Khan et al., 1999; Loveless & Koivikko, 2000; Shaywitz et al., 2002; Simos et al., 2000). The shorter latency early ERPs in dyslexia were unexpected and have not often been reported. However, we observed a similar effect in a rapid visual task (Batty et al., 2001). These results could be explained within the temporal processing dysfunction model of dyslexia (De Martino et al., 2001), wherein dyslexics have difficulty with rapidly presented stimuli, regardless of modality, and do not have the time to process them fully. More rapid, early processing of visual stimuli has also been reported in hyperactive children (ADHD), who due to their impulsivity tend to process stimuli in a superficial manner (Sunohara et al., 1999).
- 22 It was interesting that only a stimulus effect was seen at the N1b, suggesting that the processing used for this present auditory task was better reflected in the temporal ERP components, which index perceptual and discriminatory stages. The temporal peaks (N1a, N1c) are larger in children than in adults (Bruneau et al., 1997; Pang & Taylor, 2000) and appear in the current study to be more sensitive to variations in auditory processing. The ORN, however, is maximal at midline sites and did show group effects. The latency window of the ORN includes the latencies of the P1a and N1c, and as it is a subtraction waveform, it may reflect in part the effects seen more laterally.
- 23 Also as reported in ERP studies with reading tasks (e.g. Khan et al., 1999), the components that reflect early stages of processing were more sensitive to differences between dyslexic and control children, and hemispheric asymmetries. Furthermore, these data demonstrate that there is not a general dysfunction in auditory processing in the dyslexic children, but that at specific stages, particularly linked to the discrimination of the two sounds – a discrimination based on frequency analysis - there is either a superficial processing of the stimuli or increased cortical recruitment to process the stimuli correctly.

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Résumé / Abstract

Les récentes études dans le domaine de la dyslexie soulignent les difficultés des enfants dyslexiques dans le traitement rapide de stimuli auditifs complexes. Nous étudions ici la ségrégation des sons co-occurents chez des enfants dyslexiques et non dyslexiques au moyen de données comportementales et électro-physiologiques (les potentiels évoqués). Vingt deux enfants âgés de 8 à 12 ans, ont été étudiés ; la moitié présente une dyslexie phonologique. Cinq sons complexes dont la troisième harmonique peut être plus ou moins discordante par sa fréquence sont présentés, les enfants doivent indiquer s'ils entendent un ou deux sons en utilisant des boutons réponses. Les composantes reflétant les différents stades de traitement auditif précoce (N1a, b, c, P1a) ainsi que l'onde négative relative au traitement de l'objet (object-related negativity ORN) ont été mesurées. Les performances des enfants dyslexiques sont légèrement moins bonnes et leurs temps de réaction plus longs que les enfants non-dyslexiques. Les stimuli discordants évoquent des réponses plus larges ainsi que des latences retardées entre 150 et 200ms. Les dyslexiques présentent des composantes plus larges (N1a, ORN) et des composantes plus précoces (P1a, N1c) que les contrôles. Ainsi, les effets sont spécifiques de la composante mesurée ce qui suggère que toutes les étapes du traitement précoce des fréquences auditives ne sont pas affectées dans la dyslexie.

Recent models of dyslexia emphasise the difficulties for these children in processing rapid, complex auditory stimuli. We investigated concurrent sound segregation in dyslexic and non-dyslexic children, using behavioural and event-related potential (ERP) methods. Twenty-two children (8-12yrs) were studied; half of the participants had phonological dyslexia. Five loudness-matched complex sounds that had either tuned or one mistuned harmonic were presented, and the children indicated with button presses whether they heard one or two

sounds. The ERP components that reflect different stages of early auditory processing were measured (N1a, b, c, P1a) as well as the object-related negativity (ORN). The dyslexic children had slightly lower accuracy and longer reaction times than the control children. Mistuned stimuli had generally larger responses than tuned stimuli, and between 150-200ms longer latencies also. The dyslexics had larger N1a and ORN components and shorter latencies for the P1a and N1c. Thus, effects were specific to component measured suggesting that only some of the early stages of auditory frequency processing are impaired in dyslexia.

Keywords : phonological dyslexia, auditory stimuli, event-related potentials