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The impact of phonological relatedness on semantic congruency judgements in readers with dyslexia: Evidence from behavioural judgements, event related potentials and pupillometry

Ciara Egan[a,b,*], Joshua S. Payne[b,c], Manon W. Jones[b]

[a] School of Psychology, University of Galway, Ireland
[b] School of Human and Behavioural Sciences, Bangor University, Wales, LL57 2AS, UK
[c] School of Psychology, Glyndŵr University, Wales, LL11 2AW, UK

ABSTRACT

Readers with developmental dyslexia are known to be impaired in representing and accessing phonology, but their ability to process meaning is generally considered to be intact. However, neurocognitive studies show evidence of a subtle semantic processing deficit in dyslexic readers, relative to their typically-developing peers. Here, we compared dyslexic and typical adult readers on their ability to judge semantic congruency (congruent vs. inconcongruent) in short, two-word phrases, which were further manipulated for phonological relatedness (alliterating vs. non-alliterating); "dazzling-diamond"; "sparkling-diamond"; "dangerous-diamond"; and "creepy-diamond". At the level of behavioural judgement, all readers were less accurate when evaluating incongruent alliterating items compared with incongruent non-aliterating, suggesting that phonological patterning creates the illusion of semantic congruency (as per Egan et al., 2020). Dyslexic readers showed a similar propensity for this form-meaning relationship despite a phonological processing impairment as evidenced in the cognitive and literacy indicative assessments. Dyslexic readers also showed an overall reduction in the ability to accurately judge semantic congruency, suggestive of a subtle semantic impairment. Whilst no group differences emerged in the electrophysiological measures, our pupil dilation measurements revealed a global tendency for dyslexic readers to manifest a reduced attentional response to these word stimuli, compared with typical readers. Our results show a broad manifestation of neurocognitive differences in adult dyslexic and typical readers' processing of print, at the level of autonomic arousal as well as in higher level semantic judgements.

1. Introduction

Developmental dyslexia describes a specific reading impairment that is not attributable to low intelligence or lack of educational opportunity (Lyon et al., 2003). Children and adults with dyslexia read and spell less fluently and accurately, and consistently show deficits in tasks relying on phonological awareness (Lyon et al., 2003; Ramus and Szenkovits, 2008; Snowling et al., 1997; Vellutino et al., 2004). To compensate for these difficulties, dyslexic readers often resort to using their intact conceptual-level knowledge to bootstrap access to meaning from text (Hulme and Snowling, 2014; Nation and Snowling, 1998; Snowling and Hulme, 2013), an ability that distinguishes them from readers with 'poor comprehension' or specific language impairment (Bishop and Snowling, 2004). Despite this, recent eyetracking and electrophysiological research shows evidence of subtle semantic processing differences in dyslexic readers, compared with their typical reading peers, both in accessing meaning at the whole sentence level (Egan et al., 2022; Schulz et al., 2008), and in delayed responses to incongruent items in word lists (Jednoróg et al., 2010; Rüsseler et al., 2007). Here, we examine – for the first time - dyslexic and typical readers' behavioural, neural, and autonomic arousal systems as they make semantic congruency judgements, in order to obtain a comprehensive picture of group differences in access to meaning, from the earliest processes through to behavioural response. We also examine the potential for phonological information to differentially modulate the semantic congruency effect in dyslexic and typical reader groups.

In reading, the ultimate goal is to extract meaning from text, and a range of cognitive methods offer a window into the ways in which readers accomplish this, as shown in a large body of work implementing lexical decision tasks and eyetracking paradigms: (Katz et al., 2012; Rayner et al., 2006; Reichle et al., 2009). However, only in electrophysiological studies are we able to pinpoint precisely the time course and effort involved in semantic processing. In studies utilising event related potentials (ERPs), semantic processing is indexed by the amplitude of a N400 wave elicited by a sentence-final word. Over forty years of research has established that the N400 amplitude, as a measure of semantic processing, is modulated by the extent to which the target word fits the semantic context in which it is presented, with increasing

* Corresponding author. School of Psychology, University of Galway, Ireland.
E-mail addresses: ciara.egan@universityofgalway.ie (C. Egan), joshua.payne@glyndwr.ac.uk (J.S. Payne), manon.jones@bangor.ac.uk (M.W. Jones).

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negative amplitude indexing greater energy required for semantic integration (see Kutas and Federmeier, 2011 for a review). However, Egan and colleagues recently showed that the N400 effect is not modulated by semantic congruency alone, and that phonological patterning – alliteration - in simple phrases interacts with congruency to determine the N400 effect (Egan et al., 2020). Specifically, when incongruent phrases nevertheless alliterate (e.g., *dangerous diamond*), the N400 amplitude is smaller than in the incongruent non-alliterating case (e.g., *creepy diamond*), suggesting that patterns in form can create the illusion of semantic congruency. Findings from Egan et al. (2020) therefore contradict a major premise in the language sciences, that the phonological forms of words are arbitrarily associated with semantic concepts (De Saussure, 2011; Gasser, 2004; Lupyan and Winter 2018), showing instead that form can affect access to meaning. Yet, not all readers are capable of processing phonology in a manner that is efficient or automatic, raising the question as to whether this form-semantic relationship is also available to poorer readers, such as those with developmental dyslexia.

In the current study, our aim was therefore to assess whether adult readers with developmental dyslexia (a) show subtle differences in semantic processing – assessed via behavioural and neural responses to a semantic congruency manipulation – compared with typical readers, and (b) whether access to meaning was further modulated by phonological patterning, as expected from the typical reader group, or whether the decreased saliency of/reduced access to phonology in the dyslexic group would render form and semantics more independent of each other. To this end, we presented groups of age-matched typical and dyslexic readers with the paradigm used in Egan et al. (2020). Two-word phrases were manipulated orthogonally according to semantic relatedness (related, unrelated) and form repetition (alliterating, non-alliterating), as in “dazzling diamond”; “sparkling diamond”; “dangerous diamond”; and “creepy diamond”. We collected concurrent measurements of pupil dilation as well as ERPs in response to the final word, and RTs and accuracy for participants’ semantic congruency judgements. Pupil dilation (PD) indexes the recruitment of attentional resources and task-related uncertainty (Geng et al., 2015; Kang et al., 2014; Mathôt, 2018). Whilst early dilation (<1000 msec) is associated with attentional orienting, relating to stimulus saliency or novelty, later dilation (>1000 msec) is thought to reflect autonomic arousal, linked with mental effort or interest (Mathôt, 2018; Wang and Munoz, 2015; Wetzel et al., 2016).

Given the extant literature on dyslexia, we predicted that the dyslexic group would be overall less responsive to semantic congruency, manifest in attenuated N400 responses and less accurate responses in their behavioural judgements. We also predicted that the dyslexic group would be overall less responsive to phonological patterning, and that this would manifest in less influence of phonological patterning on the perception of semantic congruency, in both neural and behavioural responses, compared to typical readers. Our hypotheses in relation to the PD measurements are necessarily more tentative, given that – to our knowledge – this is the first study to take such measurements in a dyslexic reader sample. However, if dyslexic readers exhibit very early differences in their responses to print – even at the level of attentional orienting – we expected a smaller overall PD in this group, and during the later PD phase, a dampened response to semantic congruency.

2. Materials and methods

2.1. Participants

Fifty-four native English speakers were recruited for this experiment, comprising 27 typical readers and 27 readers with developmental dyslexia. These participants were recruited via the Miles Dyslexia Centre Specific Learning/Socio-communicative Difficulties Panel at Bangor University. Of the initial sample; 12 participants (4 typical, 8 with dyslexia) were excluded due to excessive alpha contamination and four additional typical readers were excluded for having verbal and/or nonverbal IQ scores more than two standard deviations below the general population mean (Wechsler, 1999). This resulted in a sample of 19 participants per group for the analyses. The ‘dyslexic’ group self-reported as having a diagnosis of developmental dyslexia ($n = 19$, 12 female, age: $M = 21.3$, $SD = 2.6$ years). The ‘typical’ group reported no history of developmental dyslexia or learning difficulty ($n = 19$, 8 female, age: $M = 22.1$, $SD = 2.9$ years). All participants had normal or corrected-to-normal vision. Ethical approval was granted by the School of Psychology, Bangor University and all participants provided written informed consent before taking part.

2.2. Stimuli and procedure

Here we used identical stimuli and procedure to Egan et al. (2020). Participants saw adjective-noun word pairs orthogonally manipulated for semantic congruency and alliteration (104 pairs per condition). Participants sat at a distance of 100 cm from the monitor, and each trial began with a drift correction (single-point recalibration) also serving as fixation in the centre of the screen. The adjective was then presented for a random duration in the range of 330–550 ms in 20 ms increments. In half of the experimental trials, the noun was then presented for 500–600 ms in random 20 ms increments. In the other half, the noun was presented for 2000 ms, allowing for collection of PD data. A response cue (#####) then prompted the participant to indicate, using a counterbalanced, binary-decision button press, whether or not the two words were related in meaning (see Fig. 1). Luminance was kept constant throughout experimental blocks, for all stimuli, fixation cues, and response prompts by manipulating the number of lit pixels via a custom Matlab script as per Egan et al. (2020) (see Fig. 2).

2.3. Background cognitive and literacy tests

In order to ensure that participants in the dyslexic group had a profile consistent with their assessment of developmental dyslexia, we administered a short battery of cognitive and literacy tests. These tests included both verbal and non-verbal IQ (expressive vocabulary and matrix reasoning) from the Wechsler Abbreviated Scale of Intelligence (WASI, Wechsler, 2011). Literacy measures with an emphasis on latency were also administered, including rapid naming (Comprehensive Test of Phonological Processing; CTOPP; Wagner et al., 1999) and word/non-word reading (Test of Word Reading Efficiency; Torgesen et al., 1999). Performance on these indices is known to discriminate typical and dyslexic readers, even in highly compensated adults (cf. Berninger et al., 2006; Jones et al., 2010). The Author Recognition Task (Acheson et al., 2008), a measure of print exposure, and a self-report measure of weekly reading times, was also included as an index of reading exposure, given evidence suggesting that participants with dyslexia typically have lower print exposure and tend to read less than typical readers (cf. The Matthew Effect; Stanovich, 2009).

2.4. Pupillometry recording

Eye movements and pupil dilation were recorded from the participant’s right eye using an Eyelink 1000 desktop-mounted eye-tracker, following 9-point calibration. Words were presented in white Arial font on a black background in the centre of a 62 × 34 cm monitor with a refresh rate of 60 Hz and a resolution of 1080 × 1920 pixels. Visual stimuli were less than 2 degrees of visual angle, to minimize the need for eye movements. Baseline correction was performed using a subtractive, pre-stimulus baseline correction (Mathôt et al., 2018). Blinks and small saccades were identified and data were marked as missing. The immediate 25 ms following a blink were also marked as missing, to allow time for pupil size to recover. Any data marked as missing were interpolated using a basic linear interpolation.

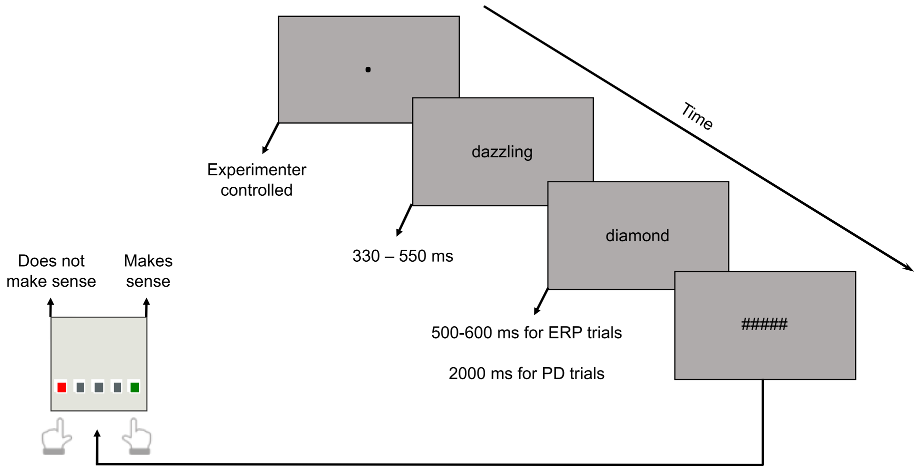

Fig. 1. Note: Schematic of the trial procedure. Reprinted from "How alliteration enhances conceptual-attentional interactions in reading," by C. Egan et al., 2020, *Cortex*, 124, :111–118. Copyright [2019]by Elsevier Ltd. Reprinted with permission.

2.5. ERP recording

Electrophysiological data were recorded at 2048 Hz with a BioSemi system, via 128 active Ag/AgCl electrodes, positioned according to the 10-10 convention. Data were resampled to 1024 Hz prior to analyses. The common mode sense (CMS) active electrode and the driven right leg (DRL) passive electrode were used as reference and ground electrodes, respectively. Horizontal and vertical electrooculograms (EOGs) were monitored using four facial bipolar electrodes placed on the outer canthi of each eye and in the inferior and superior areas of the left orbit.

Data were then pre-processed via Brain Vision Analyzer 2 (BrainVision Analyzer, 2020). Noisy electrodes were replaced by means of spherical interpolation. Data were re-referenced offline to the global average reference (average of all electrodes except for the EOGs) and filtered using a 30 Hz (48 dB/oct) low-pass and 0.01 Hz (12 dB/oct) high-pass zero phase shift filter. Data from a preliminary block in which participants were asked to make specific eye movements and blinks were visually inspected and non-ocular artefacts were discarded. Ocular correction was conducted using Independent Component Analysis (ICA, computed using the AMICA procedure; Palmer et al., 2008). Data were then segmented into large epochs centred on noun onset starting from 200 ms before stimulus onset and until 800 ms after stimulus onset. Following this, EEG signals were visually inspected and remaining noisy epochs were discarded. After baseline correction relative to a 200 ms pre-stimulus interval, epochs were averaged in each of the four conditions and grand-averages were computed. In situations wherein alpha-contamination was sufficient that early sensory components (P1/N1/P2 complex) were not visible in these grand-averages then the participants data was not included. Following pre-processing typical readers had an average of 85 trials per condition (SD = 11), and dyslexic readers had an average of 88 trials per condition (SD = 8).

2.6. Experimental design and statistical analyses

Behavioural accuracy was analysed using a generalized linear mixed model with a binomial link function, for which the fixed factors were centred and sum-coded (Nieuwenhuis et al., 2017). Fixed factors were Group (Dyslexia, Typical), Congruency (Congruent, Incongruent), Alliteration (Alliterating, Non-alliterating), and the interaction between them. A maximal slope was initially specified for 'WordPair' (1+Group | WordPair), but the model failed to converge (Barr et al., 2013). As such, the most parsimonious mixed model was used (Matuschek et al., 2017), consisting of a between-participant intercept and within-participant slopes of Congruency and Alliteration, and the contribution of their interaction. The formal specification of the model was:

Accuracy ~ Group × Congruency*Alliteration + (1+ Congruency × Alliteration | Participant) + (1 | WordPair).

ERP mean amplitudes were analysed using a mixed factorial ANOVA in the N400 time-window (300–500 ms over an average of the same 11 centroparietal recording sites as Egan et al., 2020). The between-subjects factor was Group (Dyslexia, Typical), and the within-subjects factors were Congruency (Congruent, Incongruent) and Alliteration (Alliterating, Non-alliterating).

For the pupillometry data, the timeseries was split into time-bins of 10 ms, and linear mixed effects models were run for each bin (as per Egan et al., 2020; Mathôt et al., 2017). The dependent variable comprised changes in pupil size modelled according to the fixed effects and the interaction between them. As with the accuracy data, the most parsimonious mixed model was implemented (Matuschek et al., 2017):

PupilSize ~ Group × Congruency*Alliteration + (1+ Congruency × Alliteration | Participant) + (1 | WordPair).

We considered an effect to be significant based on the t-as-z approach where $t > 1.96$ (approx. $\alpha = 0.05$) in 20 or more contiguous time bins for a minimum effect duration of 200 ms (cf. Egan et al., 2020; Mathôt et al., 2017). For data and analysis scripts please see: https://osf.io/emjg6/?view_only=1052f5947d2b49f2b139ca15a9ff1d45.

3. Results

3.1. Background cognitive and literacy tests

Background cognitive and literacy tests validated group differences on relevant measures (see Table 1). Readers with dyslexia had longer rapid naming, word, and nonword reading latencies than typical readers, as well as more word/nonword naming errors. Participants with dyslexia also had lower verbal IQ and print exposure, but both groups self-reported spending equivalent time reading in an average week. Importantly, both groups had similar nonverbal IQ.

3.2. Behavioural

Accuracy data revealed a significant fixed effect of group ($\beta = 0.87$, $SE = 0.33$, $z = 2.62$, $p < .01$), such that accuracy was lower for participants with dyslexia ($M = 75.89$, $SD = 21.19$), than for typical readers overall ($M = 85.59$, $SD = 13.84$). There was also a significant fixed effect of congruency ($\beta = -0.99$, $SE = 0.37$, $z = -2.72$, $p < .01$), such that accuracy was lower for congruent ($M = 76.19$, $SD = 15.45$) than incongruent ($M = 85.29$, $SD = 20.19$) word pairs. We also found a significant fixed effect of alliteration ($\beta = -0.47$, $SE = 0.18$, $z = -2.52$, $p <$ .05) with poorer performance for alliterating ($M = 78.36$, $SD = 18.15$)

Table 1
Scores on cognitive and literacy tests. Note: [a] Time in seconds; [b] Number of errors; [c] Number of authors (max 30); [d] Time in hours; [e] WASI subtest scaled score; *$p < .05$; **$p < .01$; ***$p < .001$.

	Mean (SD)		*t*	*Cohen's d*
	Dyslexic n = 19	Typical n = 19		
RAN [a]	17.62 (4.61)	12.89 (2.52)	3.92***	1.27
Word Reading (Acc) [b]	3.10 (2.35)	0.53 (0.77)	4.537***	1.47
Nonword Reading (Acc) [b]	10.32 (4.15)	1.84 (1.71)	8.229***	2.67
Word Reading (Time) [a]	79.47 (20.70)	53.86 (7.26)	5.09***	1.65
Nonword Reading (Time) [a]	76.49 (26.92)	52.38 (12.79)	3.525***	1.14
ART [c]	5.37 (2.49)	10.84 (5.54)	−3.926***	1.27
Average weekly reading [d]	16.31 (8.62)	16.42 (5.36)	−0.045	0.02
Verbal IQ [e]	5.47 (3.22)	8.74 (2.77)	−3.35***	−1.09
Matrix Reasoning [e]	11.32 (1.95)	11.05 (1.87)	0.425	0.14

than non-alliterating pairs ($M = 83.13$, $SD = 18.64$). There was also an interaction between congruency and alliteration ($\beta = 0.97$, $SE = 0.33$, $z = 2.98$, $p < .01$), driven by generally better performance on incongruent versus congruent trials in non-alliterating conditions. However, the interactions between group and congruency ($\beta = 0.23$, $SE = 0.67$, $z = 0.35$, $p = .73$) and group and alliteration did not reach significance ($\beta = -0.06$, $SE = 0.25$, $z = -0.25$, $p = .80$). The three-way interaction between group, congruency, and alliteration also did not reach significance ($\beta = 0.71$, $SE = 0.36$, $z = 1.96$, $p = .05$). See Fig. 2 below.

3.3. ERP

In the N400 time-window there was a main effect of congruency (F (1, 36) = 15.483, $p < .001$, $\eta^2 = 0.301$, see Fig. 3 below) with more negative going amplitudes to incongruent trials. The main effects of group (F (1, 36) = 3.496, $p = .09$, $\eta^2 = 0.070$) and alliteration (F (1, 36) = 3.039, $p = .09$, $\eta^2 = 0.078$) did not reach significance.

Although typical readers showed a trend for greater amplitude difference between congruent and incongruent trials in general compared to dyslexic readers (as illustrated via difference waves in Fig. 4 below), the group x congruency was non-significant (F (1, 36) = 3.005, $p = .09$, $\eta^2 = 0.077$). There were no other observable patterns of effects in these data. None of the other higher-order interactions were significant [group x alliteration: F (1, 36) = 0.135, $p = .72$, $\eta^2 = 0.004$; congruency x alliteration: F (1, 36) = 0.204, $p = .65$, $\eta^2 = 0.006$; group x congruency x alliteration: F (1, 36) = 0.291, $p = .59$, $\eta^2 = 0.008$].

3.4. Pupillometry

An early main effect of Alliteration was present from 70 to 350 ms, showing overall larger pupil dilation to alliterating pairs. A main effect of Congruency was seen from 1270 to 2000 ms, characterised by consistently larger pupil dilation to congruent versus incongruent trials. From 1350 to 2000 ms, a main effect of Group was seen such that Dyslexic participants showed generally reduced pupil dilation compared to Typicals. No significant interaction effects emerged. See Fig. 5 below.

4. Discussion

Here, we assessed whether adult readers with developmental dyslexia (a) show subtle differences in semantic processing compared with typical readers, and (b) whether access to meaning is further modulated by phonological patterning, as expected from the typical reader group. To this end we measured participants' behavioural accuracy (from semantic sensibility judgements), ERPs (the N400 component), and pupil dilation.

Behavioural accuracy data showed that whilst dyslexic readers showed a preserved overt congruency effect, they were less accurate than typical readers in making semantic relatedness judgements overall (cf. Schulz et al., 2008), and all readers – whether typical or dyslexic – were less accurate in judging semantically congruent items compared with incongruent items (Boutonnet et al., 2014; Egan et al., 2020; Schulz et al., 2008). This effect is likely due to the relative ease of judging that two concepts are unrelated, compared to verifying a semantic link between them (Egan et al., 2020). Of crucial relevance to our predictions, *all* readers patterned similarly in the relationship between congruency and alliteration: readers were highly accurate in rejecting incongruent *non*-alliterating phrases (e.g., creepy-diamond), but relatively less accurate in rejecting alliterating-incongruent phrases (e.g., dangerous-diamond), consistent with the assertion that alliteration

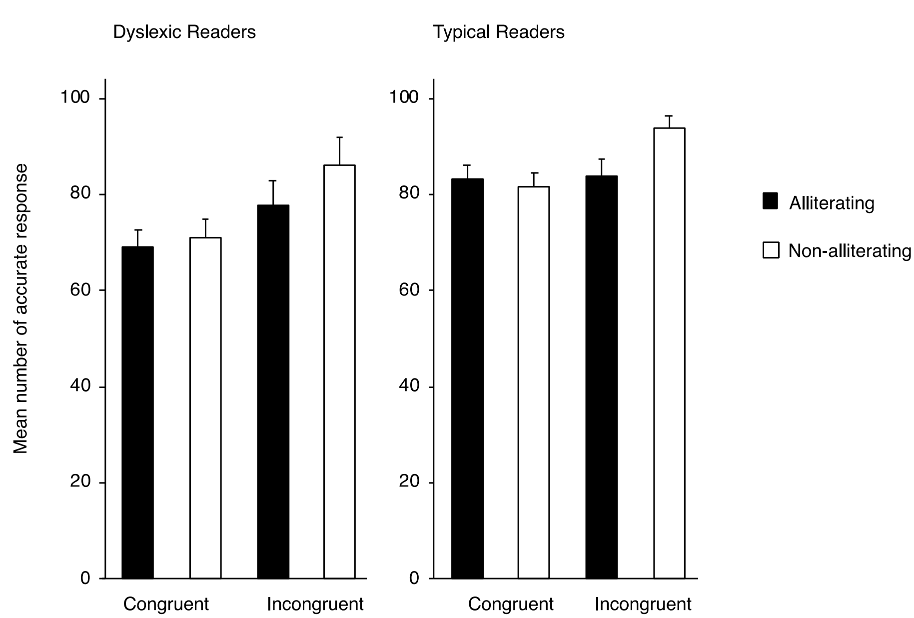

Fig. 2. Behavioural accuracy for participants with dyslexia (left) and typical readers (right), representing the number of trials (max 104) upon which participants correctly reported that phrases 'made sense' or not. Error bars depict the standard error of the mean.

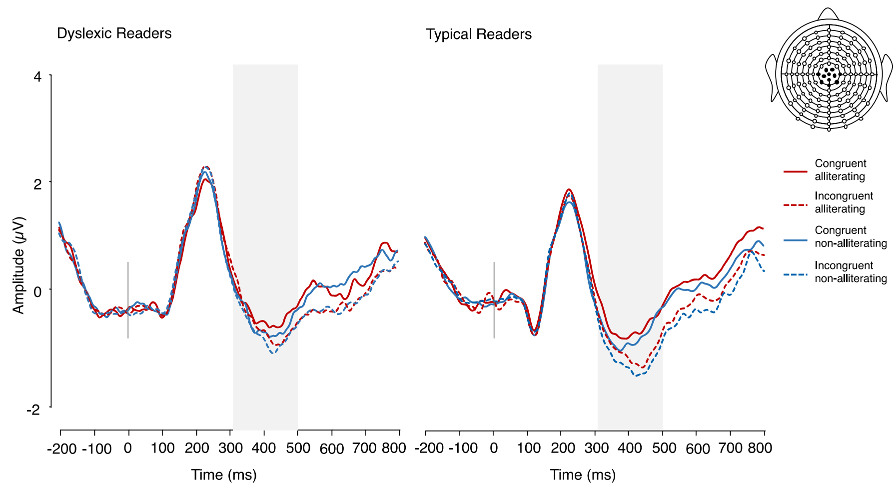

Fig. 3. Mean ERP amplitudes for participants with dyslexia (left) and typical readers (right), the shaded bars represent the areas of analysis.

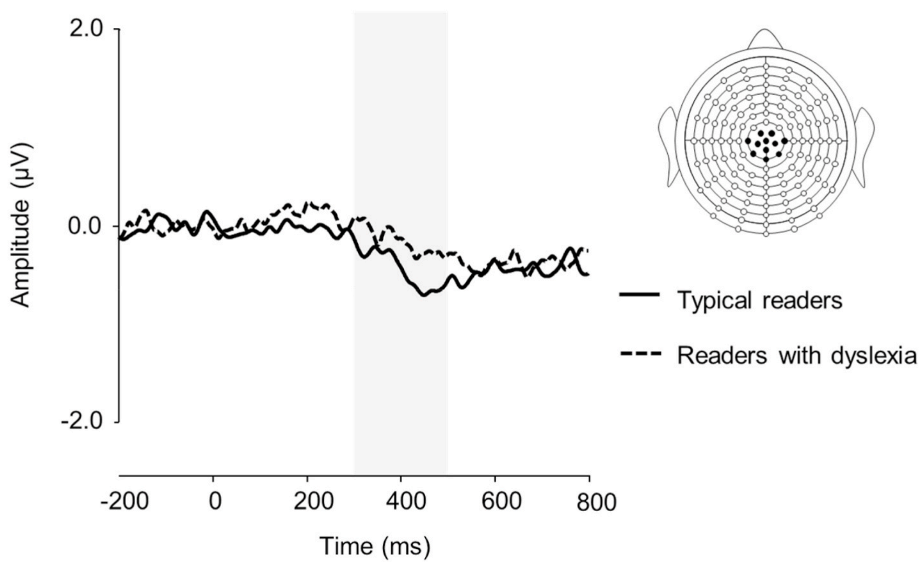

Fig. 4. ERP difference waves showing the N400 effect (congruent conditions subtracted from incongruent conditions) for participants with dyslexia (dashed line) and typical readers (solid line), the shaded bars represent the areas of analysis for the N400.

compromises participants' ability to judge a phrase as incongruent (Egan et al., 2020). The adult dyslexic readers were therefore compromised in overall semantic judgement accuracy, yet – similar to typicals - they remained sensitive to phonological patterning in phrases, which further modulated their semantic congruency judgements. Therefore, despite a likely phonological deficit, dyslexic readers showed a similar tendency to typicals in conflating similarities in sound with similarities in meaning (Egan et al., 2020).

At the neural level, whilst all readers exhibited a classic N400 effect, manifest in greater mean amplitudes for incongruent as compared to congruent items (Kutas and Federmeier, 2011), no other significant effects emerged in this analysis.

At the level of attentional orienting and cognitive engagement, we observed pupil dilation (PD) effects in two separate time windows. In an early time window (70–350 ms post noun onset) alliterating items elicited greater dilation than non-alliterating items. However, we shall avoid over-interpretation of this result, given that it is too early to reflect an attentional orientating response or a specific response to the stimuli (Mathôt, 2018; Wang and Munoz, 2015) and stimuli in this experiment were fully controlled for luminance. In a later phase of pupil dilation (>1000 ms) all participants yielded larger pupil size in response to congruent over incongruent items, consistent with Egan et al. (2020).

Moreover, dyslexic readers showed smaller pupil dilation overall than typical readers during the later phase of dilation. Pupil dilation in during this later phase (>1000 ms) can be attributed to higher-order attention/executive functioning, which can in turn be elicited by attentional or emotional engagement, or cognitive load (Egan et al., 2020; Mathôt, 2018; Partala and Surakka, 2003; Scheepers et al., 2013; Strauch et al., 2022). We consider it unlikely that this finding reflects a reduction in cognitive load, since reading is generally more effortful for readers with dyslexia than typically developed readers (Miller-Shaul, 2005; Snowling et al., 2012; Suárez-Coalla and Cuetos, 2015). Similarly, it is unlikely to reflect a reduced emotional response, as the participants were reading declarative adjective-noun pairings that were not very emotionally salient. Thus, we propose that dyslexic readers' attention system may be less engaged by these word stimuli than is the case for typical readers (Laeng et al., 2012). In other words, dyslexic readers appear to yield less autonomic arousal in response to print than do typical readers.

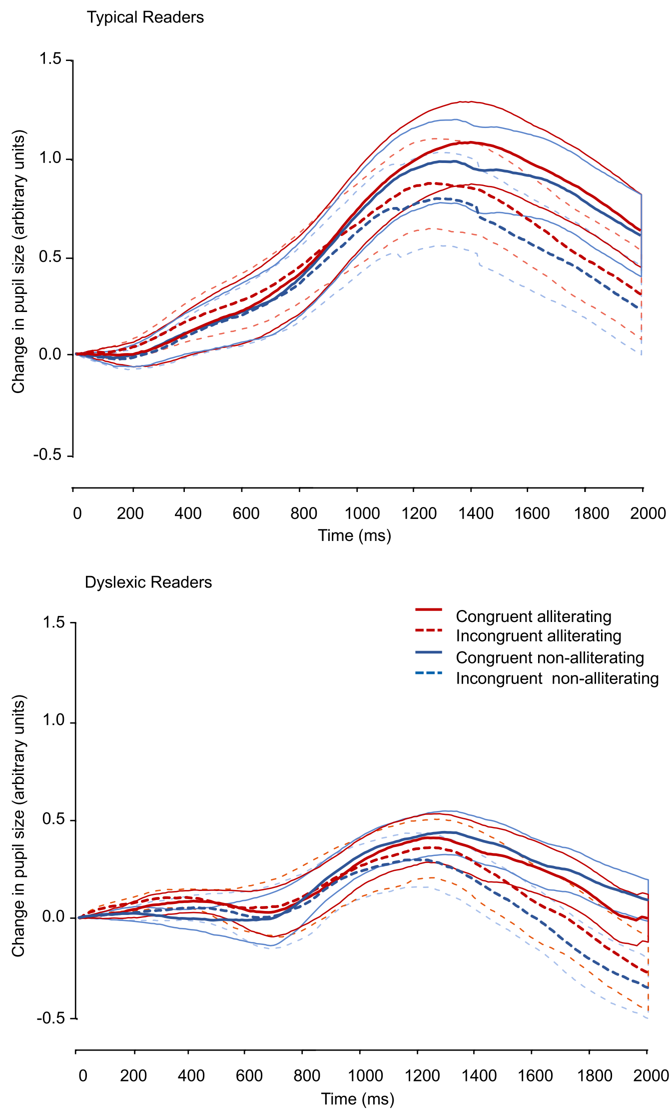

Fig. 5. Pupil dilation for typical readers (top) and those with dyslexia (bottom), the shaded areas represent the standard error of the mean.

4.1. Implications for our understanding of dyslexia and study limitations

The current findings, in relation to our hypotheses, reveal evidence of (a) a subtle semantic processing anomaly in dyslexia, manifest clearly at the level of behavioural judgement; yet (b) the effect of phonological patterning and its modulation of semantic congruency judgements that is similar to that observed in typical readers. Thus, slight differences in semantic judgements between readers of different abilities stands separately to the interaction between form and meaning, which appears intact for all readers, regardless of ability, and despite a hypothesised phonological impairment in poorer readers.

Similarly, global group differences appear in indices of autonomic arousal, in which dyslexic readers yield an overall reduction in the attention response – measured by pupil dilation - to all word stimuli compared with typical readers. This finding – which reflects the first comparison of dyslexic readers' pupillatory responses – requires further work to ascertain its origins. Whilst these findings may reflect a generalized attentional deficit (Gabrieli and Norton, 2012; Hari and Renvall, 2001; Krause, 2015; Shaywitz and Shaywitz, 2008; Laeng et al., 2012), an alternative possibility is a reduced attentional *response* in dyslexic readers, specifically to written words (Bavelier et al., 2013; Breznitz and Leikin, 2001; Franceschini et al., 2013; Horowitz-Kraus and Breznitz, 2014, 2008; Perfetti, 2007; note that the data reported here cannot speak to a capacity limitation or a deficit reflecting reduced reading experience, cf. Goswami, 2014). An interesting follow-up to determine the specificity of this effect to print would comprise a comparison of linguistic vs. non-linguistic stimuli to ascertain whether the observed effect is specific to processing text, or indeed reflects an attentional deficit.

Finally, it is necessary to mention some limitations of this study. Loss of data from a large number of participants owing to alpha contamination in the ERPs and other factors likely resulted in loss of power to detect more subtle effects. In the ERP analyses, we saw smaller N400s in dyslexic compared to typical readers, which is consistent with differences in accuracy performance between groups. Nevertheless, this interaction did not reach significance and replication is needed to clarify if this pattern of results in semantic congruency judgements is observed in other samples of dyslexic and typical readers. Despite these limitations, our data overall patterns similarly across the different measures, which indicates a relatively clear set of findings: Dyslexic readers exhibit a subtle impairment in overtly judging semantic information compared to typical readers, and this difficulty appears to be separable from their sensitivity to phonological information. We also show – for the first time – that dyslexic readers' pupil dilation is globally reduced in response to these word stimuli.

5. Conclusion

Previous research has shown that, in typical readers, phonological similarity, in the form of alliteration, can lead to the impression of semantic similarity, evident in both behavioural judgements and ERPs. Here, we aimed to assess whether this was also the case for individuals with developmental dyslexia. We found that whilst form-meaning relationships impact reading in dyslexic individuals, as with typicals, dyslexic readers nevertheless show a global reduction in the attentional response to phrasal stimuli, and a subtle semantic processing deficit. Our results show that, in adulthood, these high functioning dyslexic readers show a broad manifestation of neurocognitive differences when compared with typical readers. Whilst subtle sentence-level differences exist (e.g., at the level of semantic processing), our data shows a fundamental difference in dyslexic readers' autonomic arousal to print stimuli. We tentatively suggest that these dyslexic adults – whilst having compensated their deficits to a significant degree – remain less responsive to print exposure compared to typically developing peers.

Credit author statement

Ciara Egan: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Writing – Original Draft, Writing – Review & Editing, **Joshua S. Payne:** Software, Formal Analysis, Writing – Review & Editing, **Manon W. Jones:** Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing, Supervision.

Declaration of competing interest

None.

Data availability

Data is available on osf (link in paper)

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participant recruitment.

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