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Greek font design: identifying preferable fonts for readers with dyslexia

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The widespread adoption of modern artificial intelligence-based chatbots has revolutionised human–computer interactions. The use of these tools confirms reading as one of the primary ways of accessing information. The grapheme–phoneme conversion process is fundamental in learning to read and justifies the research for the development of tools capable of facilitating it. In the special case of a dyslexic student, the design choices related to a digital textual content cannot be a direct result of the aesthetic sense of the content creator. In this paper GreekDyslexic is presented, a Greek letter font that attempts to meet the characteristics proposed by the literature on high readability design. The production phases of GreekDyslexic are described, from the choice of elementary forms for their composition to the homogenisation process. This endeavour is driven by four key motivations: its application for native Greek speakers, its utility for learners of classical or modern Greek, the use of Greek letters in mathematics and physics, and its integration into digital museum materials. To achieve these objectives, a caption-based test is structured in which GreekDyslexic is compared to some of the most widely used fonts or those regarded as highly readable due to their sans serif nature. The test was administered to 98 Greek-speaking adults from Cyprus and Greece, 19 of whom reported a diagnosis of dyslexia. Despite being in the minority, a part of the sample rated GreekDyslexic positively. As a result, several potential solutions for future design interventions that effectively improve readability are suggested.

KEYWORDS

inclusive teaching, dyslexia, readability, font, design

1 Introduction

For a long time, many communicative technologies have been properly designed as an entity towards which a user directs a message rather than as a tool that facilitates messages between various users (Gunkel, 2012). Progressively, therefore, the ergonomic paradigm has been combined with the communicative one, moving from the creation of components capable of efficiently transmitting encoded commands to the creation of tools capable of actively participating in the construction of knowledge. Artificial Intelligence, which has contributed for a long time and in multiple areas of interest in Human-computer Interaction, through modern chatbots, could establish a bidirectional form of communication. The introduction of such tools in educational design is certainly a central theme of pedagogical research, and several experiments have confirmed both the potential (Zappalà et al., 2024) and the limitations (Di Tore et al., 2024). However, this article examines one of the most evident but less discussed aspects related to the use of chatbots, namely the primary modality through which one interacts with the machine: reading. For communication with the computer to

occur, it is indeed necessary to sustain a sequence of questions and answers, or rather prompts and results, which the user repeatedly reads, modifies, rereads, and so on. The reading process has been extensively studied across various scientific fields. Several works have led to a deep understanding of reading by identifying the main background operations (Coltheart 1978, 1981), and they anticipated one of the most well-known descriptive schemes in the scientific community: the *Dual Route Cascaded* Coltheart et al. 2001). This proposal was further developed in the work of Job and Sartori (1984), who defined the two ways: one of a direct lexical-semantic type, which establishes a one-to-one correspondence between the set of symbols that constitute the word and the respective phonological element, and the other of an indirect sub-lexical phonological type, which instead constructs the phonological output as a sequence of individual grapheme-phoneme correspondences. A reader usually unconsciously uses one of the two ways, switching based on personal parameters such as word length and familiarity (Di Tore, 2016). However, as highlighted by various studies (Ziegler and Goswami, 2005; Share, 1995), the use of the indirect way is a *conditio sine qua non* for the acquisition of reading competence. Therefore, generally, while for everyday words or those composed of frequent letter groups the direct route is preferred, for the acquisition of new words the indirect route is preferred. Fostering this conversion process, taking into account the considerable increase in the use of chatbots for knowledge construction (Pérez et al., 2020; Hwang and Chang, 2023), reinforces the need for a human computer interaction that is not only efficient but also more ergonomic, and therefore capable of adapting to the unique cognitive processes that characterize human beings.

2 Font design and readability

The study of text readability must necessarily consider multiple variables: from the physical support where the text is reproduced, therefore on paper or on screens of large or small dimensions (Huang, 2019), to the language to be used, and to the potential audience to which the text is addressed. The topic is of interest to multiple scientific disciplinary sectors, and there are numerous works in the literature that have demonstrated the crucial role of text formatting in order to increase the degree of readability (Reid et al., 2004; Rello et al., 2013; Ross, 2023). While for formatting, it is almost always possible to identify an optimal choice of parameters easily modifiable by those who produce the text, the choice of the optimal font remains an open problem. The first condition on the choice of font is certainly related to the writing system used to communicate in a certain language. As a language evolves, it requires a continuous expansion of its dictionary; hence, iconographic writing systems like Chinese inherently need to comprise a high number of glyphs. Consequently, for these glyphs to be distinguishable, they require a greater level of detail. However, the complexity of the character is functional to readability when it allows greater discrimination between the various characters, independently of aesthetic research. In the specific case of Chinese, it has been demonstrated that the less complicated a character is, the better its readability on desktop displays (Huang, 2019; Dobres et al., 2016). For this reason, for example, a simple style like the Hei style is used in experiments (Liu et al., 2016), where readability is studied as a function of stroke variation rather than font. In fact, the production of a font for languages like Chinese or Japanese requires the creation of more than 6,000 characters. Consequently, for over a decade, dynamic solutions capable of automatically generating new fonts by mediating between some well-known ones (Lian and Xiao, 2012) or using small sets as a base (Miyazaki et al., 2019) have been proposed. Strategies that seek to address the problem of optimal font choice change with writing systems different from the iconographic one, such as the syllabic or alphabetic. Problematic characters of the Sinhala script, for example, are identified as they are very similar to each other; the authors therefore propose design recommendations for a high-readability font (Subasinghe and Samarawickrama, 2024). In another work, the readability of a font for the Devanagari script is studied using an eye-tracker that allows the recording of the number and duration of fixations on precise regions of the text (Ralekar et al., 2018). Even in the case of alphabetic writing systems, the dependence of readability on the type of font chosen is confirmed, and it is interesting to observe that the result is verified in cases where both the languages and the methodologies are different from each other (Pae et al., 2017; Hejres and Tinker, 2024; Alexeeva et al., 2020; Galiano et al., 2023).

3 Dyslexia and reading challenges

Despite considerable advancements in understanding reading development and effective instructional methods, many students worldwide continue to struggle with reading (Vaughn and Fletcher, 2021). The Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5; APA, 2013) identifies "Specific Learning Disorder with impairment in reading"—commonly linked with dyslexia (Snowling et al., 2020) as persistent difficulties with accurate or fluent word reading, poor decoding skills, and inadequate spelling, even after at least 6 months of targeted intervention. This condition is further identified by below-average academic performance for one's age or the necessity for considerable effort or support to maintain average levels of achievement. These difficulties are considered unexpected, as individuals may demonstrate cognitive strengths that contrast with their reading struggles or continue to face challenges despite receiving generally effective instruction (see Vaughn et al., 2024).

The DSM-5 (APA, 2013) classifies Specific Learning Disorder with impairment in reading/dyslexia as a neurodevelopmental disorder—a heritable, lifelong condition with early onset (Snowling et al., 2020). Since 1980, numerous studies have shown that children with dyslexia often struggle with phonological processing. The most common challenges include poor phonological awareness, limited verbal short-term memory, and slow lexical retrieval (see Snowling and Hulme, 2024). However, recent theories suggest that phonological impairment alone does not fully explain the difficulties associated with dyslexia (e.g., Fella et al., 2022; Zoccolotti, 2022). Gori and Facoetti (2015) propose a potential link between dyslexia and visual crowding. Visual crowding is a perceptual phenomenon in which identifying individual letters becomes more difficult when surrounded by other letters. Supporting this view, it was found that abnormal crowding accounts for 60% of the slowed reading speed observed in Italian individuals with dyslexia (Martelli et al., 2009).

Recent research has explored ways to mitigate deficits in the visual processing of letters and words, particularly by improving reading abilities in individuals with dyslexia through specially designed fonts.

These dyslexia-friendly fonts aim to enhance letter recognition, distinguish similar letter shapes, and reduce crowding effects (e.g., Galliussi et al., 2020). Unlike traditional fonts, dyslexia friendly fonts incorporate thicker or "heavier" lines at the base of letters (Wery and Diliberto, 2017). By making individual letters more distinguishable, these design features are believed to reduce reading errors and lessen the cognitive effort required for reading. Notable efforts include the development of the EasyReading™ font by Angolo Manzoni, and a font called "Dyslexie" created by Dutch artist Christian Boer,[1] both of which aim to facilitate reading for children and adults with dyslexia.

However, the extent to which dyslexia-friendly fonts improve reading speed and accuracy compared to commonly used fonts like Arial and Times New Roman remains a subject of debate. For example, Bachmann and Mengheri (2018) conducted a study involving 533 fourth-grade primary school students to investigate whether changing the font from Times New Roman to EasyReading™ could facilitate reading for dyslexic students. The study's findings revealed a statistically significant improvement in reading fluency when using the EasyReading™ font across various reading tests, including excerpts, words, and non-words. In contrast, another study Marinus et al. (2016) examined the effects of different fonts on 39 low-progress readers learning to read in English. Participants were tasked with reading four different texts, each presented in a different font condition. Although the fonts were matched for letter display size, they varied in spacing settings. Results indicated that low-progress readers read 7% more words per minute using the Dyslexie font compared to the standard Arial font with regular spacing. However, when the spacing within and between words in Arial was adjusted to match that of Dyslexie, the improvement in reading speed disappeared. The study concluded that the effectiveness of the Dyslexie font is primarily due to its unique spacing settings rather than its specially designed letter shapes.

Yet, efforts to develop dyslexia-friendly fonts have mainly concentrated on languages such as English, Dutch, or Italian, with comparatively less attention given to creating similar resources for Greek.

4 Font design and development

The Greek alphabet consists of 24 letters, each of which has an uppercase and lowercase variant. Greek is sufficiently transparent to allow for complete, sequential alignment between graphemes and phonemes (Protopapas and Vlahou, 2009). The alphabet can be partitioned into four classes characterized by the vertical extension of the letters relative to the line. In particular, the letters "α," "ε," "η," "ι," "κ," "ν," "o," "π," "σ," "τ," "υ," "ω" belong to the standard class commonly defined by the "x-height" (Kahn and Lenk, 1998), the letters "β," "δ," "θ" belong to the ascender class consisting of letters that extend above the standard box, the letters "γ," "λ," "μ," "ρ," "φ," "χ," "ψ" to the descender class consisting of letters that extend below the standard box, therefore below the line, and in addition to these common classes also for the Latin alphabet, it is possible to determine a fourth class consisting of the letters "ζ," "ξ" which extend both above the box and below the line. The first path we chose to follow was certainly suggested by reflections concerning the presence or absence of serifs in the individual glyphs. The simple shapes of "sans-serif" fonts have no glyph embellishments and minimise the elements useful for the composition of the individual glyph and its unique distinction from all others. Due to these characteristics, it was decided to use the Arial font as a starting point for the creation of the glyphs; in particular, key lines called skeletons were extracted from the individual Arial glyphs (Zhang and Suen, 1984) to serve as a first reference point for the design of the new glyphs (Figure 1). Subsequently, a point cloud was generated using half of the glyph's contour and half by calculating the symmetrical with respect to the calculated skeleton. The same procedure was then used to determine the point cloud of GreekDyslexic (Bilotti et al., 2023), a Greek letter font created using the elementary shapes of the OpenDyslexic font. This second reference point was chosen to address the problem of reversal error, which is less studied than the Latin alphabet but, at least from a graphic point of view, also possible in the case of the Greek alphabet (Figure 1). Once the point cloud for the individual glyphs of both fonts was identified, the Coherent Point Drift method (Myronenko and Song, 2010) was applied to identify an intermediate cloud between that of Arial and that of GreekDyslexic. The intermediate cloud was then chosen manually and used as a new starting point for the design of the new glyphs. With this method, we tried to emulate the style of OpenDyslexic as much as possible; however, interventions were necessary in cooperation with people who use this alphabet daily, with the aim of homogenizing the thickening in the lower part between the letters and to respect the correct belonging to one of the four classes.

5 Methodology

5.1 Description of the questionnaire

An online questionnaire was designed to collect data on font preferences among Greek native speakers, including those with and without reading difficulties. The questionnaire aimed to gather this information in a simple and engaging manner. It was divided into three parts, each focusing on different aspects of font readability and preference. Participants rated the readability of artefact captions and mathematical formulas, each presented in four different fonts: Times New Roman, Calibri, Arial, and GreekDyslexic. They used a 5-point

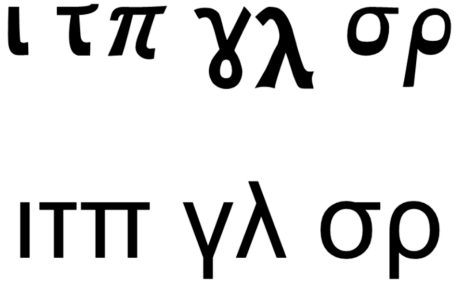

FIGURE 1
Some combinations of Arial glyphs (below) that could cause reversal error compared to GreekDyslexic glyphs (above).

1 http://www.dyslexiefont.com/en/dyslexie-font/

Likert scale (1 = "Strongly Disagree," 5 = "Strongly Agree") for both types of content.

5.1.1 Artefact captions

The first part of the questionnaire presented participants with three images of culturally significant artefacts familiar to Greek speakers from Cyprus and Greece. These artefacts were chosen to ensure cultural relevance and familiarity. The artefacts included:

i The Creation of Adam, a fresco by Michelangelo depicting God and Adam with their fingers touching.
ii A marble statue of Aphrodite from Soloi, dating back to the 1st century BC, housed in the Cyprus Museum.
iii A copper ingot from Engomi, Cyprus, dating to the 16th century BC, also located in the Cyprus Museum.

The inclusion of three artefacts served a dual purpose. First, it ensured that participants were exposed to a variety of contexts in which fonts might be used, enhancing the ecological validity of the study. Second, it allowed us to assess the consistency of participants' responses across different stimuli, thereby evaluating the internal reliability of the questionnaire as a tool for measuring font readability preferences.

5.1.2 Mathematical formulas

The second part of the questionnaire focused on the readability of mathematical formulas, a critical aspect of academic and professional communication. Two commonly used mathematical formulas were selected:

i The Pythagorean theorem: $\alpha^2 = \beta^2 + \gamma^2$.
ii A linear equation: $\psi = \omega\chi + \varphi$.

The inclusion of two mathematical formulas was intended to test the consistency of participants' responses in a different but equally important context. Mathematical notation often presents unique readability challenges, and by including these formulas, we aimed to ensure that the questionnaire could reliably assess font readability across diverse textual formats. This approach also allowed us to evaluate the internal consistency of the tool, as participants' responses to the formulas could be compared with their responses to the artefact captions.

5.1.3 Demographic information

The final part of the questionnaire collected demographic data, including participants' gender, age, and whether they had been diagnosed with dyslexia. This information was essential for analyzing potential differences in font preferences between individuals with and without dyslexia.

5.2 Procedure of administration and data collection process

A pilot study was conducted with four participants, two university students with dyslexia and two without, to assess the clarity of the questionnaire items. All text stimuli and mathematical formulas were presented at a fixed font size of 14 point, in line with recommendations from the British Dyslexia Association (2023). Line spacing and character spacing were kept consistent across all fonts. The texts and the mathematical formulas were justified to ensure uniform interword spacing throughout. The questionnaire was distributed online via email and announcements on the University of Nicosia's LMS learning platform. Participation was voluntary, and all participants were informed about the study's objectives and provided informed consent before completing the questionnaire. To ensure a diverse sample, including individuals with and without dyslexia, the research team collaborated with the University's Success Centre, which supports students with disabilities, and the Department of Distance Learning, which communicated the study to postgraduate students enrolled in distance courses.

The Success Centre and the Department of Distance Learning disseminated the questionnaire link directly to students, ensuring that the researchers did not have access to sensitive or confidential information. This approach safeguarded participants' privacy and ensured compliance with ethical standards.

5.3 Participants

A total of 98 participants completed the questionnaire. The majority of respondents were female (81.6%, $n = 80$). In terms of age distribution, 35.1% ($n = 35$) were between 18 and 22 years old, 22.7% ($n = 22$) were between 23 and 25 years old, 9.3% ($n = 9$) were between 26 and 29 years old, and 33% ($n = 32$) were over 30 years old.

Regarding dyslexia status, 73.5% ($n = 72$) of participants reported no official diagnosis of dyslexia, 19.4% ($n = 19$) reported a dyslexia diagnosis, and 7.1% ($n = 7$) were unsure of their dyslexia status.

6 Results

As shown in Table 1, GreekDyslexic consistently registers the lowest average scores across all tasks, with standard deviation values similar to those of the other fonts. This pattern remains unchanged when the sample is limited to dyslexic readers, as indicated in Table 1. The lowest ratings are particularly evident in the first three questions, which show average scores of 1.89, 2.05, and 2.11, with modal values of 1. In contrast, the highest ratings appear in the final two questions, with average scores of 2.95 and 3.05, and modal values of 5. The minimum scores for GreekDyslexic are generally comparable to those of the serif font used for comparison, except in the third question. Maximum scores are also similar to those of the other fonts, with the exception of the first question, where the maximum score is considered an outlier.

Despite being the least preferred font overall, half of the participants rated GreekDyslexic with a total average score of at least 2.5 out of 5. Additionally, 25.8% of the sample gave it an overall score of 3.5 or higher. When focusing specifically on questions related to the application of the font in mathematical expressions, the evaluations improve: 59.8% of participants rated it at least 2.5, and 44.3% rated it at least 3.5 out of 5. To assess the impact of font choice on ratings and to determine if these effects differed between participant groups, we conducted a Two-Way Mixed ANOVA (Group: Dyslexic/Non-Dyslexic as a between-subjects factor; Font: Arial, Calibri, GreekDyslexic, Times New Roman as a within-subjects factor).

TABLE 1 Mean font scores across different captions (standard deviation in parentheses) calculated for the entire sample (values in black) and dyslexic readers only (values in blue).

Font	Task 1: Adam	Task 2: Aphrodite	Task 3: Copper	Task 4: Pythagorean theorem	Task 5: Linear equation
TimesNewRoman	3.50 (1.17)	3.49 (1.17)	3.39 (1.13)	4.14 (1,12)	3.98 (1.24)
	3.11 (1.10)	3.00 (1.15)	3.36 (1.12)	3.79 (1.51)	3.68 (1.53)
Calibri	3.91 (1.00)	3.85 (1.04)	3.84 (0.96)	4.22 (1.00)	4.17 (1.03)
	3.52 (1.02)	3.53 (1.22)	3.57 (1.02)	3.94 (1.18)	4.00 (1.00)
Arial	4.24 (0.96)	4.27 (0.87)	4.26 (0.89)	4.17 (1.07)	4.27 (1.09)
	3.84 (1.06)	4.16 (1.01)	3.94 (1.03)	3.58 (1.35)	3.95 (1.47)
GreekDyslexic	2.50 (1.36)	2.48 (1.39)	2.50 (1.42)	3.00 (1.52)	2.96 (1.41)
	1.89 (1.15)	2.05 (1.35)	2.11 (1.45)	2.94 (1.72)	3.06 (1.54)

Regarding the software, all statistical analyses will be conducted using the R programming environment (version 4.5.0) with RStudio (version 1.1.456), making use in particular of the afex package for mixed ANOVA and the emmeans package for post-hoc tests. The average ratings of the four fonts, obtained from questionnaire responses, were used as the dependent variable. The results revealed statistically significant main effects for both factors. A main effect of the Group was observed ($F(1,88) = 4.20$, $p = 0.043$), indicating an overall difference in ratings between dyslexic and non-dyslexic participants, albeit with a small effect size. Additionally, a highly significant main effect of Font was found ($F(2.06,181.45) = 56.39$, $p < 0.001$), demonstrating that the four fonts were rated significantly differently at a global level, with a large effect size. Crucially, the analysis showed that the interaction between Group and Font was not statistically significant ($F(2.06,181.45) = 0.03$, $p = 0.969$). This suggests that the influence of a particular font on ratings does not significantly change between the two groups. Given the significant main effect of Font and the non-significant interaction, Bonferroni post-hoc tests were performed on the estimated marginal means of the Font factor to identify which fonts differed significantly at a global level (i.e., averaged across groups). The results indicated a clear hierarchy of preference as shown in Table 2.

7 Discussion

The results revealed that GreekDyslexic consistently received low preference ratings across all tested tasks. Both dyslexic and non-dyslexic participants rated it lower on average, suggesting that the typeface may not align with user expectations or offer optimal reading comfort. These findings indicate that commonly used fonts may be more effective for readers with dyslexia than fonts specifically designed for them. This preference for familiar typefaces over dyslexia-specific designs is consistent with previous research on languages that use Latin alphabets (Kuster et al., 2018; Rello et al., 2013). Unlike the other fonts, GreekDyslexic showed a growing trend in ratings in successive questions, which is reflected in a corresponding increase in average scores (Figure 2). This trend is consistent with the greater impartiality observed regarding font preference in dyslexic individuals, whom we can hypothesize are much more sensitive to readability issues. Beyond personal aesthetic sense, which might drive preference for one font over another, the functional nature of a font remains paramount as a technology providing access to a non-natural human ability that must therefore be learned. Regarding the higher ratings recorded for mathematical tasks, the causes can be multiple and more complex. The proposed mathematical formulas, being composed of a small sequence of letters, do not require the activation of orthographic competence, thereby reducing grapheme-phoneme conversion to individual glyphs. These glyphs, when taken individually and not in word-groups, may appear more pleasing and legible.

8 Limitations and future research

To build on these findings, several promising directions for future research emerge. First, the findings may not be as broadly applicable as they may be due to the small sample size ($N = 98$) and the disproportionate presence of participants with dyslexia (19.4%) in comparison to those without (73.5%). Future research would improve the validity of comparisons between these groups by using a larger, more balanced sample. Furthermore, Times New Roman, Calibri, and Arial were the fonts chosen for comparison since they are often used in Greek-language contexts. However, their familiarity might have generated bias since, rather than objective readability, participants' preferences might have been impacted by prior experience. By including unconventional fonts or a wider range of dyslexia-friendly typefaces, further study could lessen this. To ensure better accessibility in the future, subsequent questionnaires should be designed with layouts tailored to the specific font in use. The questionnaire's design, which only included quantitative scores and no open-ended questions, is another limitation. Although the Likert-scale responses yielded valuable information on readability perception, they failed to record participants' justifications for their choices or recommendations for font enhancements. Qualitative input could help guide future improvements to the GreekDyslexic font and provide deeper insights into user experiences in future research. Additionally, real-world font usage includes a broader range of materials, including longer continuous text, whereas the study evaluated readability in the context of mathematical formulas and artefact captions. A more thorough assessment of the font's suitability for various reading situations might be possible by increasing the range of text formats in future trials. In addition, the reliance on self-reported dyslexia status also presents a potential limitation, as some participants may have been undiagnosed or uncertain about their condition. Future studies could enhance diagnostic accuracy by incorporating standardised screening tools

TABLE 2 *p*-values of the font comparisons obtained from the *post-hoc* test.

Font	TimesNewRoman	Calibri	Arial	GreekDyslexic
TimesNewRoman	–	0.0012	0.0002	<0.0001
Calibri	0.0012	–	0.0423	<0.0001
Arial	0.0002	0.0423	–	<0.0001
GreekDyslexic	<0.0001	<0.0001	<0.0001	–

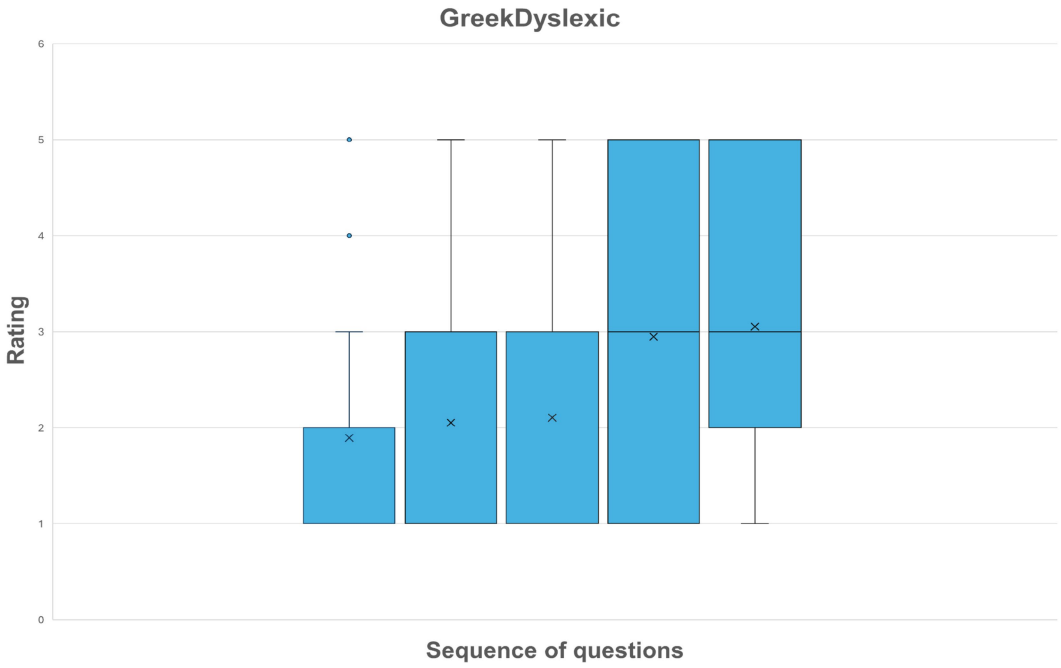

FIGURE 2
Boxplots of the GreekDyslexic font ratings by dyslexic readers only, across the sequence of the five questions.

alongside self-reports. Controlled experiments comparing reading speed, accuracy, comprehension, and visual fatigue between GreekDyslexic and other fonts could complement subjective ratings with objective performance metrics. Neurocognitive approaches, such as eye tracking or EEG, may shed more light on how typeface affects visual processing and cognitive burden, particularly in dyslexic readers. Cross-linguistic research should further investigate whether the benefits of GreekDyslexic apply to bilingual environments (e.g., Greek-English speakers), given that dyslexia manifests differently across languages. Furthermore, participatory design approaches, such as workshops with dyslexic users, could provide direct feedback to help enhance the font's features. Finally, investigating the font's performance in digital environments—such as e-books, educational apps, or dynamic text displays—would address the growing need for accessible typography in screen-based media.

9 Conclusion

This study introduced GreekDyslexic, a specifically designed font to support readers with dyslexia. In this work is described the entire process of realisation of the font, from the study of the potential users to the identification of consistent shapes and design guidelines for the creation of the glyphs and from the creation of a primitive shape through the morphing method to the modality of the choice for final glyphs. A first test is conducted to compare GreekDyslexic with three of the most commonly used fonts among individuals both with and without dyslexia. The results analysed from the collected data agree with the literature, and GreekDyslexic is not preferred to other fonts, but the choice of font remains statistically significant, and several actions to improve readability are highlighted. Notably, this research marks the first initiative of its kind focused on the Greek language, filling a significant gap in the literature on accessible typography.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and

institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

UB: Software, Writing – original draft, Formal analysis. KD: Methodology, Investigation, Writing – original draft. AF: Investigation, Writing – review & editing, Methodology, Supervision, Conceptualization. MT: Project administration, Conceptualization, Writing – review & editing, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomp.2025.1610349/full#supplementary-material

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