<u>Come and Paint my World:</u>

<u>Grapheme-colour synaesthesia in native Polish speakers</u>

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Research Project 1 (26 EC)

Research Master in Brain and Cognitive Sciences

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"If you take *framboise* in French, for example, it's a scarlet color, a very red color. In English, the word *raspberry* is rather dull, with perhaps a little brown or violet. A rather cold color. In Russian it's a burst of light, *malinovoe*; the word has associations of brilliance, of gaiety, of ringing bells."

– Vladimir Nabokov, multilingual writer, translator, and synaesthete.

Abstract

Grapheme-colour synaesthesia is a phenomenon in which the perception of letter or grapheme units elicits the concurrent experience of a specific colour. Cross-language research on this phenomenon has shown that general patterns of letter-colour associations can be explained by various perceptual, statistical and semantic mechanisms, called regulatory factors (RFs); however, the influence each RF has on synaesthetic associations varies between languages. This thesis presents the first investigation of Polish-speaking synaesthetes and associated RFs. I find evidence of several perceptual and linguistic influences on Polish, including the first report of an effect of phonological similarity on colour in a language with a Latin-based script. Furthermore, I demonstrate that Polish speakers tend to associate multi-letter graphemes as having a singular colour and discuss how these findings might aid in understanding the temporal dynamics of synaesthesia, and the computational stages of reading overall. The findings highlight the importance of conducting cross-language investigations in synaesthesia research.

Keywords: digraphs, grapheme-colour synesthesia, linguistics, Polish language.

Acknowledgements

This thesis could not have been written without the invaluable help and support I received at the University of Amsterdam. I would like to thank the staff of the Brain and Cognitive Sciences Research Master, Vincent Tijms and Anna Holland, who promptly and comprehensively answered any and all questions I had while working on this project. I would also like to thank my internal assessor, dr Romke Rouw, whose impressive research output on synaesthesia forms the foundation of most of my work. Last but certainly not least, I am immensely grateful to my daily supervisor, dr Nicholas Root, for his expert guidance and invaluable insights on all phases of this project, from hypothesis formation and literature search to data analysis and writing. His mentorship and encouragement have been instrumental in successfully completing this project. I owe the successful completion of this thesis to his assistance and his unwavering belief in my abilities as a beginner researcher.

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Introduction

Grapheme-colour synaesthesia is a neurosensory phenomenon in which the experience of written linguistic units (i.e. letters, digits, or logograms like Chinese *hanzi* or Japanese *kana*) induces concurrent colour associations, e.g. "P is sky blue", or "C is bright yellow". These experiences are real (Palmeri et al., 2002), involuntary (Mattingley, 2009), and persisting (Asher et al., 2006). Synaesthetic associations *coexist* with the inducing stimulus without replacing them; in other words, a synaesthete experiences both the physical colour of the printed letter, as well as the associated synaesthetic colour (Ward, 2013). Ever since the earliest scientific reports of synaesthesia in the early 1800s, this phenomenon has been used as a "window" to further understand how our brains integrate multisensory information to create the conscious experience (van Leeuwen et al., 2015). Synaesthesia has also been suggested to be useful in understanding higher-level cognitive phenomena like art, creativity, or language (Ramachandran & Hubbard, 2001). This thesis will demonstrate how studying grapheme-colour synaesthesia can aid our understanding of the cognitive processes underlying reading, with special attention given to similarities and differences between different languages.

Regulatory factors in grapheme-colour synaesthesia

Individual grapheme-colour associations were traditionally thought to be largely idiosyncratic, i.e. while one synaesthete might associate the letter D with the colour brown, a different one might perceive it as having a lilac hue. Nonetheless, studies recruiting large samples of synaesthetes have found that some grapheme-colour pairings occur more frequently than others. For example, English-speaking synaesthetes tend to associate the letter "A" with the colour red (Root et al., 2018; Simner et al., 2005) and "Y" with the colour yellow (J. L. Mankin & Simner, 2017; Rich et al., 2005), while lesser-used letters of the English alphabet (e.g. X and Z) are associated with less luminant, more muted colour categories like black or grey (Simner et al., 2005a; Watson et al., 2012). Furthermore, some associations appear to be based on letter-colour pairings perceived early in childhood, such as on refrigerator magnets (Witthoft et al., 2015; Witthoft & Winawer, 2006). These patterns suggest that letter-colour associations do not arise only from intrinsic characteristics of the inducers (e.g. letter shape), but can also be influenced by other linguistic and cultural factors.

These findings have led to the development of research on regulatory factors (RFs) – perceptual, linguistic, and cultural mechanisms that appear to govern the formation of grapheme-colour associations (Asano et al., 2017; Root et al., 2018, 2021). These factors explain not only within-language pairings, but also offer an explanation as to why they vary across languages. Using a large sample of synaesthetes from seven linguistic backgrounds, Root et al. (2021) reported that non-linguistic influences, such as the shape of the individual graphemes, appear to be influential across the different languages studied, while more cultural and semantic influences (e.g. Y is yellow because "yellow" starts with Y; Root et al., 2018; Simner et al., 2005) exert differing amounts of control across languages. Furthermore, the influence of different RFs appears to also vary based on the internal rules of the language. For example, grapheme-colours associations in English, a language with deep orthography (the same letters and letter combinations can be pronounced in different ways), appear to be influenced by visual cues, rather than by the phonological properties (Brang et al., 2011; Watson et al., 2012). In contrast, synaesthetes who speak languages with more consistent spelling-pronunciation mappings, like Japanese and Korean, are more likely to experience associations are more influenced by the pronunciation of graphemes (Asano & Yokosawa, 2011; Kang et al., 2017). If variations in RFs relate to the internal rules of the given language, it is possible that the synaesthetic colours "mirror" the letter representations that underlie the reading process of speakers of the language.

Interestingly, the RFs that influence grapheme-colour associations in synaesthetes also influence implicit associations in non-synaesthetes. Even though non-synaesthetes generally do not experience graphemes as having a certain colour, when they are forced to choose colours for graphemes, they tend to choose the same colours as synaesthetes (red for “A”, yellow for “Y”, etc.), albeit without the high internal consistency seen in synaesthetes (Simner et al., 2005; Wrembel, 2007, 2009). Given that both synaesthetes and non-synaesthetes share certain patterns of associations, then maybe what makes synaesthesia a unique phenomenon is not the propensity to associate graphemes with colours, but rather the propensity to *consciously* experience them. Cross-cultural research on RFs underlying grapheme-colour associations (both in synaesthetes and in non-synaesthetes) might therefore help us to understand how written language representation differs across languages and writing systems.

The colours of words and morphemes

In this thesis, I also want to explore how synaesthetic experiences relate to the reading process. While most research on grapheme-colour synaesthesia in languages using alphabetic scripts (such as English, Dutch or German, as well as Russian and Greek) has concentrated on colours induced by the perception of individual letters, an interesting body of research has investigated the synaesthetic colour of whole words. In general, synaesthetes tend to experience words as having a single colour, rather than as a combination of separately-coloured letters. These words are often “coloured” by the initial or otherwise salient letter (i.e. all the letters in “cat” are the colour of “c”; Simner et al., 2006). Consistent with previous studies on the RFs in the language, English-speaking synaesthetes tend to be influenced by the shape of the initial letter, rather than its pronunciation (e.g. “cat” and “cite” have the same colour, but “cite” and “site” do not; Baron-Cohen et al., 1993; Paulesu et al., 1995). However, more recent studies on compound words have shown that whether one word is perceived as one colour also depends on a number of linguistic factors. For example, English-speaking synaesthetes tend to experience more frequent compound words as one word unit (and therefore one colour) in comparison to less frequent ones (Blazej & Cohen-Goldberg, 2016; J. Mankin, 2018; J. L. Mankin et al., 2016).

These findings suggest that larger language units (either in the form of whole words, or – in the case of compound words – constituent morphemes) can “override” existing letter-colour associations. This is supported by recent electrophysiological evidence that synaesthetic experiences occur at a later processing stage than colour and letter perception (Teichmann et al., 2021). This raises the question of whether synaesthetic associations also occur at the intermediate level between letter and morpheme: do multigraphs – combinations of multiple letters that produce one phoneme, such as digraphs (two letters; e.g. *sh* in English) and trigraphs (three letters; e.g. *sch* in German) – have their own synaesthetic colours? To my knowledge, even though the typically-used name is *grapheme*-colour synaesthesia (most likely used to be inclusive of non-alphabetic languages), it is an open question whether letters (i.e. excluding multigraphs) and graphemes (i.e. including multigraphs) elicit distinct synaesthetic colour experiences.

Rationale and hypotheses

To date, the influence of RFs on synaesthetic has been studied in languages including English, German, Dutch, Spanish, Japanese, Korean, Russian and Greek (Asano & Yokosawa, 2013; Root et al., 2018, 2021). However, there appear to be no peer-reviewed reports of synaesthetic experiences (much less any influences on them) in native Polish speakers. This thesis will present the first large-scale study on grapheme-colour synaesthesia in Polish speakers and investigate perceptual, statistical and semantic RFs underlying these synaesthetic experiences.

In brief terms, Polish is a Slavic language that belongs to the Indo-European family and utilises a Latin script consisting of 32 letters (35 if counting X, V and Q, which are only used in foreign words; see figure 1). Alongside letters common to other European languages like

English or Dutch, Polish employs several letters that have diacritic marks (including the overdot, stroke, and ogonek; for an overview, see Wells, 2000). Letters with diacritics (e.g. Ą, Ę, Ć, Ń) are considered to be their own letters, separate from their non-diacritic counterparts. In popular culture, Polish is often described as heavily relying on consonant clusters. In reality, several multi-letter units ("multi-letter graphemes", or "multigraphs") are used to represent specific, singular sounds. Polish also differs from English by its relatively transparent letter-to-pronunciation mappings (however, not as transparent as in the case of Italian or Japanese; Scheppert et al., 2017). These specific characteristics of Polish orthography will be expanded on later in this thesis.

Aa Ąą Bb Cc Ćć Dd Ee Ęę
Ff Gg Hh Ii Jj Kk Ll Łł Mm
Nn Ńń Oo Óó Pp (Qq) Rr
Ss Śś Tt Uu (Vv) Ww (Xx)
Yy Zz Źź Żż

Figure 1. The Polish alphabet. Letters in parentheses are only used in foreign words.

First, I will conceptually replicate studies investigating the influence of several different RFs on grapheme-colour associations, characterizing the relative contribution of each RF to synaesthetic associations in Polish. Furthermore, I take advantage of a particular feature of Polish orthography – certain letter combinations that act as separate graphemes or multigraphs depending on context – to test whether Polish synaesthetes experience *letter*-colour or *grapheme*-colour associations.

In summary, I will study the following RFs:

1. Perceptual RFs: letter shape (similarly shaped letters are more likely to evoke similar colours) and pronunciation (similarly pronounced letters are more likely to evoke similar colours; Brang et al., 2011)

2. Statistical RF: frequency (more frequently-used letters are more likely to evoke more luminant colours; (Beeli et al., 2007),
3. Semantic RFs: Colour Term ("B is brown because brown starts with a B"; Simner et al., 2005) and Index Route ("B is yellow because bees start with B, and bees are yellow"; Mankin & Simner, 2017).
4. Graphemic RF: letter clusters that are pronounced as one sound will be more likely to evoke one singular colour experience, rather than each letter having its own colour.

A more detailed background and rationale behind every RF will be discussed in their separate chapters. These findings will be discussed in terms of findings from other languages (Brang et al., 2011; Root et al., 2018, 2021)

The dataset

Participants

The data used in this study comes from a cohort of native Polish speakers recruited via word-of-mouth and advertisement on the web. Self-described synaesthetes, self-described non-synaesthetes, and people unsure of their synaesthetic status were all encouraged to take part.

Participants filled in a custom-made colour-picker survey hosted on the online platform Qualtrics (Root, 2021). The survey was based on the popular synaesthesia test battery by Eagleman et al. (Eagleman et al., 2007). Each of the 35 letters used in the Polish alphabet was presented a total of three times; within each repetition cycle, the order of letters was randomized. Participants selected the colour they most strongly associate with the letter using a colour wheel. Answers were recorded in HSL space, which describes colour using three coordinates related to the dominant wavelength (hue), saturation (chroma) and brightness/luminosity of the colour (Schwiegerling, 2004), and subsequently converted to coordinates in CIELuv space. This colour space was selected because of its high sensitivity and specificity for determining synaesthetic status in comparison to other spaces (Rothen et al., 2013; Rouw & Root, 2019).

We calculated the participants' test-retest consistency, as operationalized by the average sum of Euclidean distances between the CIELuv components between the three repetitions. Synaesthetic status was assigned to participants with a test-retest consistency of <135 (Rothen et al., 2013). Using this operationalization, 64 out of 112 participants were determined to be synaesthetes.

Additional tasks. Alongside the main colour-picking task, the participants were also presented with additional surveys that were not analysed as part of this thesis. This included confidence scores after each trial, demographic information, and foreign language proficiency. Additionally, after the main colour-picker task, the participants completed a questionnaire on their synaesthetic experiences of multi-letter graphemes.

Preprocessing and outlier removal

After calculating consistency scores, we removed responses to letters that are not typically used in the Polish alphabet unless used in foreign words (i.e. Q, V, X), as they were not relevant to the hypotheses described in this thesis. Next, to remove potential outliers (e.g. misclicks), we first calculated the mean coordinates in colour space for each letter per participant. Then, we determined the distance of each trial from the mean. If a trial was more than 45 CIELuv units away from the mean, the trial was removed and the mean was recalculated.

Perceptual properties: Visual and phonological similarity

One way in which researchers have studied the mechanisms underlying synaesthetic experiences has been by examining the relationships between perceptual various characteristics of pairs of inducing graphemes (e.g. shape, frequency, phonology) and the concurrent colours. Brang, Rouw, Ramachandran and Coulson (2011) found that similarly shaped letters in the Latin script tend to evoke similar colour associations. Studies on Japanese and Korean have found that similarly pronounced graphemes tend to evoke similar colour associations (Asano

& Yokosawa, 2011; Kang et al., 2017); as previously stated, such an effect was not found in English (Asano & Yokosawa, 2013), suggesting that this effect is moderated by orthographic depth.

Like English, Polish uses a Latin script; therefore, we can hypothesize that synaesthetic pairings in the language will be influenced by letter shape. At the same time, unlike English, Polish has largely consistent spelling-pronunciation mappings (though not always consistent pronunciation-spelling mappings; Scheppert et al., 2017), which suggests that, like Japanese and Korean, it might also be influenced by the phonology of its letters and graphemes.

Methods

Sound similarity. Phonological similarity between two letters was operationalized as phoneme distance calculated using the Shared Natural Classes method (Frisch et al., 1997). This measure determines relative proportions for each grapheme-phoneme correspondence by linking Polish word frequency (calculated from a Polish News corpus; Leipzig Corpora Collection, 2019) to Polish pronunciation (from the Phoible project; Nikolaev, 2019). This enables pronunciation similarity for *letters* (rather than phonemes) to be calculated, by multiplying the similarity of each possible pair of phonetic realizations for two letters by the relative frequency of that pair. A higher proportion of shared natural classes indicates that the letters are similarly pronounced.

Visual similarity. Visual similarity between two letters was derived from the confusability of a feedforward neural network derived from open-source code from Testolin et al. (2017). The network was trained on natural images and designed to mimic how the human brain recognises written letters, from the encoding of low-level visual features to letter identity recognition. By extracting the predictions from the model's readout layer, we were able to compute a confusion matrix between letter pairs. Just like with the sound similarity measure, higher confusability indicates a higher degree of visual similarity between the letters.

Data analysis. The methods employed largely replicated the analysis pipeline that Brang et al. (2011) used to test the Visual Similarity RF in English. For each synaesthete, we calculated the distance matrix for synaesthetic colours (CIELuv distance between each letter pair). This distance matrix was then correlated with the phonological and visual similarity matrices, and the resulting Pearson's correlation coefficient was Fisher z-transformed. Unlike Pearson's r, Fisher's z-transformed r is normally distributed, allowing us to use a t-test to test the hypothesis that the average r in our sample differs from zero (Fisher, 1915).

For both sound and visual similarity RFs, the correlation was calculated between a measure of dissimilarity (Euclidean distance in colour space) and a measure of similarity (phonemic/visual closeness). Therefore, if the two RFs have a positive effect on synaesthetic associations, we can expect the correlation between them to be negative.

Results

Table 1 shows the synaesthetes' mean Fisher-transformed correlations for the visual and sound similarity RFs.

Table 1. Descriptive statistics for Pearson correlation coefficients associated with the visual similarity and sound similarity RFs.

	Mean r	S.D.
Visual similarity	-0.088	0.063
Sound similarity	-0.057	0.088

In order to see whether group-level effects were significantly different from zero, we conducted two one-sample t-tests (see table 2). The results were highly significant against the Bonferroni-adjusted alpha of 0.025 for both the visual similarity ($t(63) = -11.089$, $p < 0.001$, $d = -0.642$) and sound similarity RFs ($t(63) = -5.139$, $p < 0.001$, $d = -1.386$). The associated Cohen's d values indicate that the mean corrected r values were 0.642 (sound similarity) and 1.386 (visual similarity) standard deviations from zero.

Table 2. One-sample t-test and effect size (Cohen's d) for the phonological similarity and visual similarity RFs.

	t	**df**	**p**	**Cohen's d**
visual	-11.089	63	< .001	-1.386
sound	-5.139	63	< .001	-0.642

Discussion

Studies on synaesthesia in speakers of languages such as English, Japanese or German have found an effect of perceptual characteristics of letters and logograms on the concurrent colour associations. Letter/grapheme shape and frequency in usage appear to be more consistent RFs among various languages; phonological characteristics, however, only appear to have an effect in languages with consistent spelling-pronunciation mappings ("shallow orthographies"). Consistent with the hypothesis that orthographic depth moderates the strength of the phonological RF, we found that in Polish (a language with relatively shallow orthography), similarly sounding letters evoke similar colour associations. To our knowledge, these were also the first results to suggest an effect of phonological similarity on a language that uses the Latin alphabet. Prior studies looked at Japanese and Korean, which have their own syllabary and featural writing systems, respectively. Since Polish uses largely the same writing system as English, the presence of the effect in one rather than the other further indicates that the difference in the phonological RF is due to the features of the language, rather than the features of the alphabet.

Due to the exploratory nature of the study, we decided to investigate the effect of both visual and phonological similarity on the synaesthetic experience of Polish letters. We implicitly treated these two measures as independent of each other without first checking for collinearity; in English, certain letter pairs that are visually similar also tend to produce similar phonemes (e.g. B and D and M and N; Manning, 1977). Future studies should take this into account and check whether visual and phonological similarity is correlated for Polish letter pairs.

Statistical property: Frequency RF

Alongside the findings on perceptual RFs, several studies have found that synaesthetic associations tend to be influenced by the statistical rules of a given language. In both German and English synaesthetes, more frequent letters (e.g. "E") tend to elicit more luminant colours in comparison to less-frequent letters (Beeli et al., 2007; Smilek et al., 2007; Watson et al., 2012). However, the results of these studies might have been confounded by the effect of *ordinality* factors: the influence of the letter's or grapheme's position in the alphabet or syllabary. In an investigation by Watson et al. (2012), luminance did not appear to be affected by ordinality; however, as pointed out by Root et al. (2018), ordinality might have a non-linear effect, with only the most salient positions in the alphabet (i.e. the beginning and end) affecting the colour experience. Given the strong overlap between some of the least-used letters in the English alphabet and the ones at the end of the alphabet (e.g. Z, Y, X; see figure 2B), it is possible that these two effects might have been confounded in prior investigations.

Polish uses largely the same letters and *in general* has similar patterns of letter frequency to English (e.g. the most common letters in both languages are vowels), but letters that have a further position in the English alphabet, like Z or Y, are much more frequent in Polish (see 2A). At the same time, several letters that are at the beginning of the Polish alphabet (like Ą, Ć, Ę) are relatively infrequent. Thus, the frequency RF in Polish is plausibly less confounded by ordinality than in English.

a) Polish single letter frequencies (in %)

A	9.02	I	8.09	R	5.06
Ą	0.95	J	2.26	S	4.46
B	1.39	K	3.54	Ś	0.58
C	3.96	L	2.36	T	3.94
Ć	0.26	Ł	1.82	U	2.59
D	3.23	M	2.73	W	4.78
E	7.51	N	5.81	Y	3.70
Ę	0.98	Ń	0.21	Z	5.17
F	0.41	O	7.90	Ź	0.07
G	1.54	Ó	0.89	Ż	0.66
H	1.25	P	2.92		

b) English single letter frequencies (in %)

A	8.55	L	4.21	W	1.83
B	1.60	M	2.53	X	0.19
C	3.16	N	7.17	Y	1.72
D	3.87	O	7.47	Z	0.11
E	12.10	P	2.07		
F	2.18	Q	0.10		
G	2.09	R	6.33		
H	4.96	S	6.73		
I	7.33	T	8.94		
J	0.22	U	2.68		
K	0.81	V	1.06		

Figure 2. Single letter frequencies (in %) for Polish (A) and English (B) sourced from the website Practical Cryptography (http://practicalcryptography.com/cryptanalysis/letter-frequencies-various-languages/)

Methods

Relative frequency (in percentages) of every letter irrespective of position in a word was derived from the website Practical Cryptography, which generated the frequencies using data sourced from the Leipzig Corpora Collection (approximately 90 million characters; Leipzig Corpora Collection, 2019). Next, the correlation between mean luminance (i.e. the “L” coordinate) and relative frequency of the letters was calculated for every synaesthete and subsequently Fisher-corrected. Since both the measures describe dissimilarity between letters, I predict that the mean correlation between the difference in luminance and the difference frequency in frequency for every letter pair will be positive.

Results

Table 3 shows the synaesthetes’ mean correlations for the frequency RF. As expected by my hypothesis, the mean Pearson’s r indicates a positive correlation between luminance and frequency.

Table 3. Descriptive statistics for Pearson correlation coefficients associated with the frequency RF.

	Mean r	S.D.
Frequency	0.082	0.183

Just like in the case of the perceptual RFs, a one-sample t-test was conducted to see whether the mean correlation is significantly different from zero. As seen in table 4, the results of the t-test were highly significant, $t(63) = 3.525$, $p < 0.001$, $d = 0.441$.

Table 4. One-sample t-test and effect size (Cohen's d) for the frequency RF.

	t	df	p	Cohen's d
frequency	3.525	63	< .001	0.441

Discussion

The results suggest an influence of the frequency RF on the experience of luminance in Polish grapheme-colour synaesthetes. We found that, similarly to prior findings in English and German, Polish-speaking synaesthetes tend to associate more frequently-used letters with more luminant colours (Beeli et al., 2007; Smilek et al., 2007). However, in order to be able to fully disentangle the effect of ordinality on the frequency RF, a future study could conduct an additional analysis between colour experience and ordinal position in the alphabet.

Interestingly, the majority of the most infrequently used letters in the Polish alphabet are ones with diacritic marks (e.g. Ć, Ń, Ź). Prior studies on Japanese and Bengali (Root et al., 2020, 2021) have noted that diacritic marks have consistent effects on the colour experiences relating to the "base" symbols; a subsequent analysis could investigate whether the various kinds of diacritics used in Polish also significantly affect the synaesthetic experience, including the luminosity of the concurrent colours.

Semantic properties: Colour Term RF and Index Route RF

Alongside perceptual and frequency-related characteristics of the inducing letters, synaesthetic associations have been found to reflect semantic and cultural patterns and idiosyncrasies of various languages. Early research on English-speaking synaesthetes found that some letters tend to elicit associations whose colour terms start with the same letter as the inducer; in other words, R tends to be red, Y tends to be yellow, and so on (Rich et al., 2005;

Simner et al., 2005a). Root et al. (2021) studied the relative influence of the Colour Term RF across seven languages and found that colour terms influence synaesthetic associations in some – but not all – languages: there was a significant Colour Term RF in Dutch, English, Japanese, Korean, and Russian, but not in Greek and Spanish.

If "Y" elicits the thought of "yellow", do other letter-word associations similarly elicit the synaesthetic experience? Mankin and Simner (2017) found that experiences of English-speaking synaesthetes tend to exhibit a general pattern of letter–prototypical word and prototypical word–colour associations. For example, A is typically red, because A stands for "apple", and apples are red. This pattern is known as the Index Route RF and appears to influence synaesthetic associations in English, Dutch, Greek, Japanese, Spanish, and Russian, but not in Korean (Root et al., 2021).

Here, we use identical methods to Root et al. (2021), extending their analysis of the Colour Term and Index Route RFs to Polish. Given that both RFs influence synaesthetic associations in languages that are relatively similar to Polish in terms of grammar (Russian) and the Latin alphabet (English, Dutch, Spanish), we expect that both RFs will have a statistically significant influence on synaesthetic associations in Polish.

Methods

Since the Colour Term and Index Route RFs are related to colour categories (e.g. red, blue), rather than coordinates in colour space. Therefore, each trial that was not deemed an outlier had its CIELuv coordinates converted into one of the 11 Berlin-Kay colour categories using the *Colournamer* algorithm (Mylonas & Macdonald, 2013). For every synaesthete, the most frequently-occurring category throughout the trials was determined to be the colour category for the letter. In cases where a synaesthete chose three different colours for a letter, the category of the first trial was used. Additionally, since the two RFs were related to the first letter of words, we removed trials pertaining to letters that are never word-initial (in Polish, these are Ą, Ę, and Ń).

Table 5. Berlin-Kay colours used in Polish and their English translations. Note that for the purposes of replicability and generalizability to previous studies, the first letter (in parentheses), rather than grapheme, was used to generate Colour Term and Index Route predictions.

Colour term (English)	Colour term (Polish)
Black	Czarny (C)
White	Biały (B)
Grey	Szary (S)
Red	Czerwony (C)
Orange	Pomarańczowy (P)
Yellow	Żółty (Ż)
Green	Zielony (Z)
Blue	Niebieski (N)
Purple	Fioletowy (F)
Pink	Różowy (R)
Brown	Brązowy (B)

Colour Term RF. This part of the analysis was a replication of a multilanguage study by Root et al. (2021). A comprehensive treatment can be found in their manuscript, but in short, their method calculates three values:

1. $matches_{observed}$, the number of letter-colour associations in the data that are consistent with the RF
2. $matches_{possible}$, the number of letter-colour associations in the data that *could* have been consistent with the RF (e.g. the number of letter-colour associations in the data that are the initial letter of a Polish Basic Colour Term)
3. $matches_{expected}$, the number of letter-colour associations in the data that would be expected by chance: even if synaesthetic letter-colour associations are completely random, some proportion will naturally appear to be consistent with an RF.

These three values are then used to construct a binomial test of the hypothesis that more letter-colour associations are consistent with the RF than would be predicted by chance: we conclude that an RF has an effect on Polish synaesthetic associations if the observed proportion $\frac{matches_{observed}}{matches_{possible}}$ is significantly higher than the expected proportion $\frac{matches_{expected}}{matches_{possible}}$.

Index Route RF. I first generated a list of Index Route predictions by conducting two questionnaires with non-synaesthetic native Polish speakers. In the first study, participants ($N_{non\text{-}synaesthete}$=28) were asked to generate up to five index words that start each letter of the Polish alphabet (excluding Ę, Ą, Ń, but including Y, which is only used as the initial letter in loanwords like “yeti”). In the second study, the top three most popular words (top two in the case of Y) were selected and presented to a different set of participants ($N_{non\text{-}synaesthete}$=26), who were instructed to pick which colour category they associate with each index word. We determined the top most likely colours as predicted by the Index Route RF by combining information about the frequency with which each word was generated with the frequency with which each colour was chosen for each word. Reporting either of these two colours for the letter was operationalized as a “match” when calculating $matches_{observed}$. The expected and observed pseudo-R^2 values were then calculated in the same manner as for the Colour Term RF.

Results

A binomial test indicated that significantly more letter-colour associations were consistent the for Colour Term RF than would be expected by chance (p < .001; table 6). The Risk Ratio is the most interpretable effect size of the test, indicating that the initial letter of a colour term is on average 1.63 times more likely than other letters to be associated with that specific colour term. Likewise, the observed pseudo-R^2 for the Index Route RF was significantly higher than the expected pseudo-R^2, $p < .001$, $RR = 1.61$ (see table 6). 29% of all synaesthetic associations are consistent with the index route, 1.61 times as many as would be expected by chance.

Table 6. Descriptive statistics for the Colour Term and Index Route RFs in Polish.

RF	Expected proportion	Observed proportion	p-value	Risk Ratio
Colour Term	0.11	0.18	$p < .001$	1.63
Index Route	0.18	0.29	$p <.001$	1.61

Discussion

Synaesthetic associations can be influenced by language-specific semantic factors, such as the initial letter of the colour names (Colour Term RF; Simner et al., 2005) or prototypical words associated with every letter (Index Route; Mankin & Simner, 2017). We replicated the analysis by Root et al. (2021) and found evidence for both RFs in the Polish language, similar to English, Dutch and Russian.

By strictly replicating the analysis for the Colour Term RF from Root et al. (2021), we failed to account for the effect of the initial *grapheme*, rather than the initial letter. *Czarny* (black) and *czerwony* (red), for example, indeed start with the letter C, but the letter is followed by the letter Z, making the cluster a digraph (*CZ*) that is pronounced differently than its constituent letters. It is possible that this oversight might have led to the generation of "false positive" predictions for the Colour Term RF.

Multigraph perception

As stated previously, a characteristic of the Polish language that makes it interesting for synaesthesia research is its heavy reliance on multi-letter graphemes. Alongside the 32 letters that make up the Polish alphabet, Polish also uses several multi-letter clusters (multigraphs) to represent singular sounds (e.g. rz, sh, dź). Awramiuk (2006) divided Polish multigraphs into two groups based on their phonological consistency; we have translated them into determinate graphemes (*grafemy stałe*) and indeterminate graphemes (*grafemy niestałe*). Determinate graphemes are two-letter consonant clusters that are pronounced as one sound regardless of their word placement, e.g. *rz* (pronounced as /ʐ/, identical to the Polish letter *ż*) or *dż* (/d͡ʐ/). Indeterminate graphemes, on the other hand, are pronounced as one sound only if they occupy a specific position in the word. For example, the digraph *zi* is pronounced as two sounds (/ˈʑi/) if it appears at the end of the word or if it's followed by a consonant; for example, in the case of the word for winter, *zima* (/ˈʑi.ma/). However, if *zi* is followed by a vowel, the *i* palatalizes the preceding letter but is not actually pronounced, as seen in the word for seed, *ziarno* (/ˈʑar.nɔ/). It should be noted that *z* (or any other consonant) is not palatalized when followed by any other vowel than *i*; see *zabawa*, fun (/zaˈba.va/).

Grapheme and letter perception during reading. Studying the synaesthetic experience of graphemes may help elucidate a major unknown in the study of the cognitive processes underlying reading: are letters or graphemes the primary representational units guiding the reading process? So far, studies investigating this have shown conflicting results. While some suggest that multi-letter graphemes are not processed in the early stages of reading (Lupker et al., 2012), others point to graphemes, not letters, as the main perceptual unit during reading (Bolger et al., 2009; Fischer-Baum & Rapp, 2014; Marinus & de Jong, 2010; Rey et al., 2000). Recent studies have attempted to consolidate these conflicting findings by comparing results from different word recognition tasks (Chetail, 2020) or by running stochastic simulations on data from older studies (Perry, 2022). Graphemes appear to show either null or weak word unit effects, suggesting that while they might be useful in guiding reading, they are nonetheless processed in later perceptual stages.

Studying synaesthetic experiences of grapheme units could prove useful in consolidating these conflicting results and studying how grapheme perception contributes to reading. Taken together, findings on the synaesthetic experiences of compound words, cross-language investigations of RFs, and recent evidence from EEG and MEG studies (Teichmann et al., 2021), are all consistent with grapheme-colour synaesthesia being a higher-level phenomenon that arises from a combination of bottom-up/early-stage perceptual and topdown/late-stage semantic levels of processing. Therefore, it might be useful to investigate whether synaesthetic experiences occur at the level of grapheme units, rather than letters.

Hypothesis and rationale. In this part of the study, I investigate how Polish synaesthetes experience determinate multi-letter graphemes and how these experiences compare to synaesthetic associations of indeterminate graphemes. I hypothesize that Polish-speaking synaesthetes will be more likely to experience determinate multi-letter graphemes as having one colour (instead than every letter being uniquely coloured) in comparison to indeterminate graphemes.

Methods

Materials and stimuli. The following multi-letter grapheme stimuli were used in the study:

1. Determinate: rz, sz, ch, dż
2. Indeterminate: ni, si, dzi

After completing the main part of the experiment (Root, 2021), participants were presented with the grapheme stimuli in a randomized order with no repetitions and asked to choose which of the following options best describes their colour experiences:

1. No colour experience (the participant just seeds the colour the stimulus is printed in)
2. Every letter is experienced in its original colour
3. The whole stimulus is experienced in the colour of the first/second/third letter
4. The whole stimulus is experienced in one colour that is different from the colours of the individual letters

Participants who chose option 4 were then redirected to the colour picker (Root, 2021). Additionally, participants were provided with a text box in case their experience did not match any of the above options.

Data preprocessing. We removed responses in which participants experienced no colour for the given stimuli. This means that only data from 43 synaesthetes out of the 64 was analysed. Next, we recoded responses into two options: single-coloured stimulus or multi-coloured stimulus. Some participants reported that they experienced a coloured gradients for a stimulus, with two distinct colours mixing or combining in the middle. Due to difficulties in interpreting and classifying such experiences, these responses were also excluded from the final statistical analysis.

Results

We conducted a Chi-squared test of independence to see whether the distribution of colour experiences differs between the two conditions (one colour or multiple colours per stimulus). Consistent with our hypothesis, determinate graphemes are 1.2 times more likely to be perceived as having one rather than multiple colours, $\chi^2(1)=4.921$, $p=.027$, $RR=1.209165$ (see figure 3).

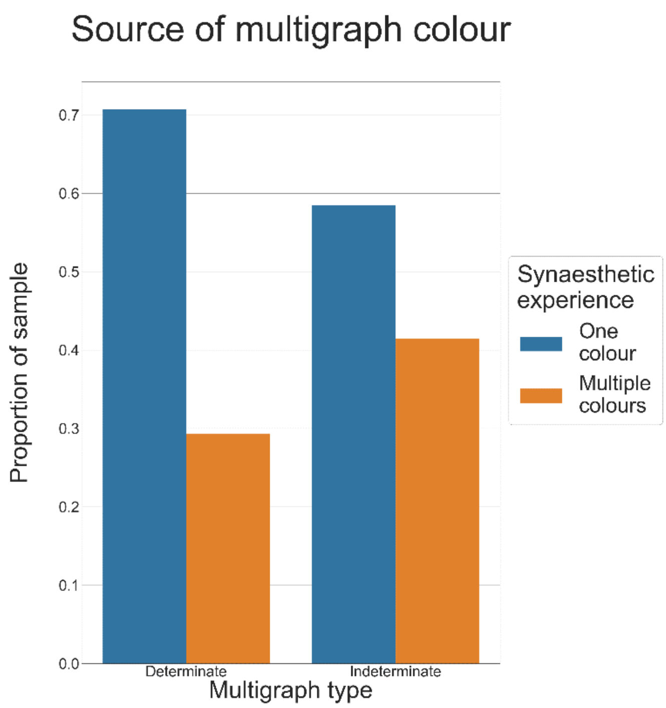

Figure 3. The distribution of singular colour and multiple colour answers for determinate and indeterminate graphemes.

Discussion

Previous research on grapheme-colour synaesthesia has found that phonological properties of letters and logograms influence colour experiences in languages with shallow orthographic depth like Japanese or Korean (Asano & Yokosawa, 2013; Kim et al., 2018); based on these findings, we hypothesized that native Polish-speaking synaesthetes would perceive multi-letter graphemes (multigraphs) that are pronounced as one sound as having one colour. We found preliminary evidence that supports this hypothesis: Polish-speaking synaesthetes were more likely to perceive determinate graphemes (i.e. multi-letter combinations that are most typically pronounced as one sound), rather than indeterminate graphemes (i.e. combinations that are only pronounced as one sound if followed by a vowel), as having one colour.

Our results can be interpreted in at least two ways. Firstly, they lend credence to the theory that graphemes, rather than letters, are the primary unit guiding reading (Marinus & de Jong, 2010; Rey et al., 2000). Alternatively, our study might suggest that synaesthetic associations arise at later stages of reading than the perception of individual letter units, as suggested by Testolin et al. (2017). Crucially, our study has been the first to directly study multigraph perception in grapheme-colour synaesthetes.

Exploratory post-hoc analysis. The initial hypothesis was based on the assumption that multigraphs are perceived differently than morphemes or words. In other words, we did not control for the fact that some determinate graphemes, just like words, could merely be "coloured" with the initial or otherwise salient letter. In order to confirm that synaesthetic experiences can really occur at the level of multigraphs, we re-ran our analysis with the hypothesis that determinate graphemes would be more likely to have one *unique* colour that is different than the colour of its constituent parts (for a detailed overview, see Kolodziejczyk et al., 2022). We found that while the majority of both indeterminate and determinate graphemes have either separate colours or one colour that is the same as that their letters, determinate graphemes are 1.70 times more likely to have a unique colour than indeterminate ones (see figure 4).

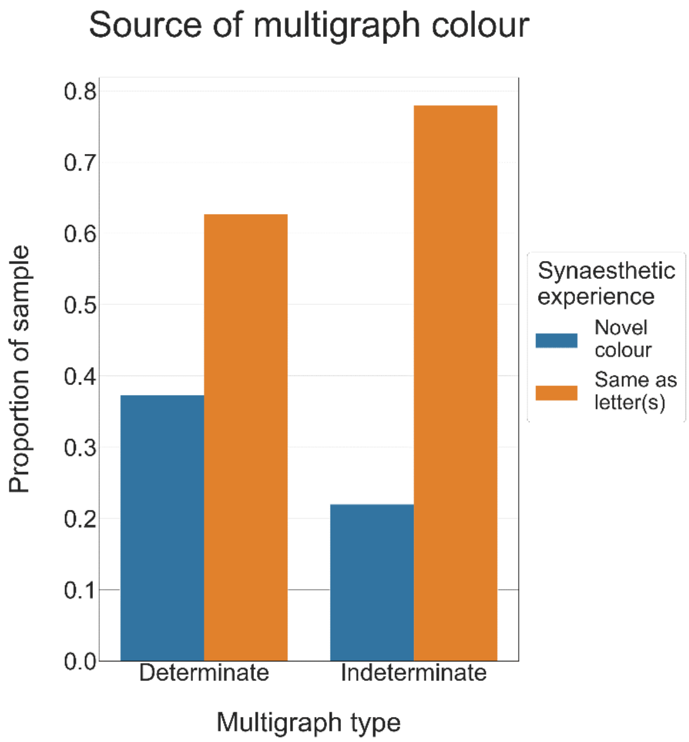

Figure 4. The distribution of one colour answers (new or derived from constituent colours) determinate and indeterminate graphemes (adapted from Kolodziejczyk et al., 2022).

Two kinds of synaesthesia? While conducting this analysis, we noticed individual differences in the proportion of multigraphs experienced as having unique and distinct colours. While some synaesthetes experienced almost every multigraph as having a unique colour, others experienced no distinct colours for any digraphs or trigraphs. We interpret these results as preliminary evidence of two distinct types of synaesthesia: "true" grapheme-colour synaesthesia (with experiences occurring at the level of graphemes) and what could more precisely called letter-colour synaesthesia, in which letters (not multigraphs) are the eliciting stimuli. At the same time, these distinct experiences could also be caused by individual differences in the computational stages of the reading process; where letters might be the principal unit directing reading for some individuals, graphemes could be for others. More research, however, is needed to investigate the plausibility of these two interpretations.

General discussion

The aim of this thesis was a comprehensive exploration of perceptual and semantic mechanisms behind letter-colour and grapheme-colour associations in a sample of Polish synaesthetes. We replicated several prior studies on mechanisms underlying colour associations (regulatory factors, RFs; Asano et al., 2017) in speakers of other languages. This included studies on the effects of the visual and phonological properties of letters, (Brang et al., 2011), relative frequency in everyday usage (Beeli et al., 2007; Smilek et al., 2007), as well as the effect of colour terms (Root et al., 2021; Simner et al., 2005) and prototypical "index words" (Mankin & Simner, 2017; Root et al., 2021). Furthermore, we described and analysed a novel RF: the extent to which synaesthetes experience colours at the level of multi-letter graphemes rather than individual letters.

To our knowledge, we collected responses from the first sample of Polish-speaking synaesthetes to date. We found that, similar to prior research in English speakers, letter-colour associations in our sample are influenced significantly by visual similarity (similarly shaped letters are associated with similar colours) and relative frequency (more frequent letters elicit more luminant colour associations). Consistent with prior research in languages with shallow orthographies, similarly pronounced letters evoked similar colour experiences in Polish speakers. Finally, we found that Polish-speaking synaesthetes were more likely to perceive determinate graphemes (i.e. multi-letter combinations that are most typically pronounced as one sound), rather than indeterminate graphemes (i.e. combinations that are only pronounced as one sound if followed by a vowel), as having one colour. This suggests that graphemes, rather than letters, may be the primary unit at which synaesthetic associations occur. Our exploration using the same data but a refined hypothesis (Kolodziejczyk et al., 2022) has found even more evidence towards that theory.

Despite the significant contributions of this study to synaesthesia research, there are still several potential limitations that should be addressed. These limitations were discussed in detail in the specific sections of each hypothesis. In summary, future research should aim to account for potential collinearity between visual and phonological similarity, disentangle the effects of ordinality and frequency on the brightness of synaesthetic associations, and account for initial graphemes, rather than letters, when forming letter-colour predictions based on semantic features of Polish. Additionally, the synaesthetic status of participants was determined using a measure based on research of English-speaking synaesthetes (Rothen et al., 2013). Recent cross-language research, however, suggests that test-retest consistency in synaesthetes varies from language to language, and that the exact threshold for synaesthetic status should be modified based on population (Root, 2022).

Conclusion

This thesis discusses various perceptual, statistical and semantic mechanisms underlying grapheme-colour associations in a first ever investigation of Polish-speaking synaesthetes. I found both remarkable similarities as well as interesting differences between factors underlying Polish associations in comparison to prior findings in other languages, further demonstrating the need for cross-language and cross-cultural comparisons in synaesthesia research.

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