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The Role of Learning in Grapheme-Color Synesthesia: A Literature Review

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Abstract:

Grapheme-color synesthesia is a perceptual phenomenon in which individuals, known as synesthetes, automatically experience the perception of a particular color when viewing a specific grapheme, forming an inducer-concurrent relationship. This unique phenomenon has intrigued researchers for decades, leading to numerous studies that aims to uncover its underlying mechanisms, including research from neurological perspectives to cognitive perspectives. One crucial aspect that has attracted significant attention is the role of learning in shaping this inducer-concurrent relationship. Hence, this literature review aims to explore various perspectives on how learning influences this condition through the examination of empirical research, theoretical models, and neurobiological evidence.

Keywords: Grapheme-color synesthesia, learning, inducer-concurrent relationship

1. Introduction

Synesthesia is a phenomenon with a mixed experience of senses (Cytowic, 1989), where the stimuli in one sense elicit an automatic and consistent experience of another sensation, forming an inducer-concurrent relationship.

Synesthesia, derived from Greek words meaning "together" and "sensation," was first documented in the 19th century. Early reports described synesthesia as an ability acquired from and maintained by the frequent exercise of learning these inducer and concurrent associations (Galton, 1880). Sir Francis Galton hypothesized synesthesia as a "use it or lose it" phenomenon. By comparing brain to muscles, which are strengthened by frequent exercise, he proposed that the repetitive training of experiencing specific sensations would reinforce the implicit relationship between inducers and concurrents, while the lack of training would reversely lead to the decline of concurrent sensations. This idea addressed the significance of learning in the maintenance of synesthesia. However, following the development of neuroimaging technology, the mainstream in the scientific community switched from a cognitive explanation to a neurobiological explanation, suggesting that synesthesia is not learned but is the result of neural basis. (Cytowic, 1989; Harrison and Baron-Cohen, 1997; Ramachandran and Hubbard, 2003). Nevertheless, contemporary research focusing on the impact of learning in shaping synesthetic experience began to flourish recently, with researchers arguing that learning is a critical component of synesthetic development (Simner et al., 2009a; Witthoft and Winawer, 2013). This contemporary research recognizes

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it as a genuine cognitive phenomenon while admitting its correlation with specific neural structures. However, the underlying mechanism of synesthesia is still being debated, thus, this literature review aims to reveal the role of learning in the formation and development of synesthesia, specifically on a type known as grapheme-color synesthesia.

Being considered as the most common and well-studied form of synesthesia, grapheme color synesthesia is defined as the perception of a particular color when viewing a specific letter or number. For instance, letter 'A' may appear red and number '4' may appear blue in the eyes of grapheme-color synesthetes. Meanwhile, although these grapheme-color associations vary among different synesthetes, they mostly remain stable over time, displaying a sense of coherence. (Simner et al., 2005). Affecting around 1.2% of the general population (Carmichael et al., 2015), it is seen as a relatively rare but rather important phenomenon for understanding how different sensory experiences are integrated. (Simner et al., 2006).

2. Theories of Synesthetic Development

Scientists have put forward different theories to explain the formation and development of grapheme-color synesthesia, ranging from genetics to environmental factors. Understanding these theories is key to interpret how learning play its role.

From a biological perspective, some theories suggest that synesthesia can be inherited from families, thus, indicating it as a genetically related phenomenon. (Baron-Cohen et al., 1996; Galton, 1880). Research has found potential genetic markers linked to synesthetic traits (Bailey and Johnson, 1997), but no single gene has been located as the main determinant of synesthesia. Therefore, although the genetics theory provides a biological background for this phenomenon, they do not offer full explanation for the individual difference showed in synesthesia to researchers.

Another theory from a neurological perspective is the neural cross-wiring hypothesis. This idea suggests that synesthesia happens because of unusual connections between neighboring brain areas that process different senses. The direct model made by researchers assumes that synesthesia is due to the direct cross-activation between a brain region processing inducer stimuli and a brain region processing concurrent responses (Ramachandran & Hubbard, 2001). In grapheme-color synesthesia, there may be increased connectivity between the visual word form area (VWFA) in the fusiform gyrus, which is the inducer area, and color-processing regions like V4, which is the concurrent area. In another indirect model, although there is also an assumption of a cross-activation between the inducer and concurrent areas, this crosstalk is thought to be moderated by a higher-order cortical area. Hence, the research indicates that synesthesia occurs through a mechanism of cross-activation, leading to reproducible, automatic, systematic perceptual experiences.

Although the genetic study of synesthesia implies that grapheme-color synesthesia can run in families (Galton, 1880), evidence also shows that the concurrents induced by particular stimuli appear idiosyncratic due to the fact that, for different synesthetes, the same inducer triggers a distinct concurrent. Therefore, it seems farfetched that a genetic blueprint would specify the synesthetic color induced by each letter, since letters and numbers are learned instead of innately specified (Marks & Odgaard, 2005). Hence, researchers hypothesized that learning is more likely to be involved in developing specific inducer-concurrent pairs, where the early learning experiences are expected to bring about such consistency within the synesthetic associations. (Rich et al., 2005)

Learning-based theories argue that synesthetic associations develop through exposure and experience during critical periods of childhood development (Witthoft & Winawer, 2013). This perspective suggests that early educational materials, such as colored alphabet books, could influence the formation of grapheme-color mappings.

Additionally, the specific learning patterns during childhood development may have crucial impacts on the inducer-concurrent relationships in grapheme-color synesthesia. Asano and Yokosawa (2012) track such relationships in Japanese synesthetes, who typically learn the Hiragana scripts before the scripts of Katakana or Kaji. However, instead of being influenced by the shapes or order of the characters, the synesthetic colors associated with Kanji and Katakana graphemes are more affected by how they sound, similar to the Hiragana script. This shows that for these Japanese speakers, their synesthetic experiences are shaped by implicit learning, which helps them create connections between characters in the different scripts.

3. Empirical Evidence on Learning and Synesthesia

There is strong evidence for addressing the impact of learning in constructing synesthetic associations. Research shows that experiences during childhood are particularly important in forming these inducer-concurrent relationships. For example, a study by Witthoft and Winawer (2013) examined 11 synesthetes and found that their grapheme-color links closely matched the colors of popular refrigerator magnets they had as children. This highlights how early visual experiences can shape synesthetic perceptions.

Longitudinal studies tracking the synesthetic development of young synesthetes support the idea that learning plays a certain role in the development of grapheme-color synesthesia. Simner and Bain (2018) found that the synesthetic associations children made became more consistent and detailed as they grew older. This research states that synesthetes aged 6 to 7 have coherent synesthetic associations with about 35% of letters, increasing to approximately 70% in age 10 and 11. Hence, there is a minimum 4-year period where the inducer-concurrent relationship between graphemes and colors are in flux. This provides evidence for the hypothesis suggesting that grapheme-color synesthesia develops through a process of refinement driven by ongoing learning.

Cultural context also plays an important role in forming synesthetic experiences. A study of synesthetes from various linguistic backgrounds found that their grapheme-color pairings differed according to language-specific features (Rich et al., 2005). One example is that Japanese synesthetes often matched colors with kanji characters differently than English-speaking synesthetes did with Latin alphabets, showing how language structure can influence synesthetic associations.

Furthermore, some experimental studies show that learning can impact synesthesia in adults as well. Non-synesthetic adults were trained to link specific colors with particular letters over several weeks. The participants started to show synesthesia-like experiences, indicating that learned associations can temporarily induce synesthetic perceptions (Colizoli et al., 2012). This finding highlights the plasticity of human brain which can be shaped by implicit associative learning, and shows how learning can artificially lead to synesthetic experiences even in adulthood.

4. Inducer Categories Triggering Grapheme-color Synesthesia

According to previous research, the inducers that contribute to grapheme-color synesthetic experience can be categorized into four main series: semantic, acoustic, visual, and ordinal properties.

4.1 Semantic

An intuitive interpretation of the first-order inducer-concurrent relationship, in which the presence of a grapheme directly brings about the perception of color, is the semantic association. Research demonstrates that the name of color significantly affects the concurrent color of these colors. For example, “R” is more likely to be red, and “Y” is more often yellow due to “r” and “y” being the first letter in these color names. (Rich et al., 2005; Simner et al., 2005)

In addition, another statement for the semantic associations is that the prototypical color of a word is likely to influence the inducer-concurrent relationship if it is frequently associated with a specific grapheme. In these cases, “D” is brown, which can be since “D” is for dogs, and dogs are usually brown (Mankin and Simner, 2017). To examine these hypotheses, they analyzed data from a word-generation experiment involving non-synesthetic participants to identify the most frequent grapheme-color semantic associations, which they called index words. They also collected data from another group of subjects to ascertain the most typical color linked with those index words. Their findings showed that the prototypical color of the index words accurately predicted the most commonly associated color for 15 out of 26 graphemes, significantly surpassing what would be expected by random chance.

The semantic property among the several inducers can be considered as mostly related to learning, as the formation of a consistent, one-to-one mapping in the inducer series and concurrent associations between the semantic meaning of certain words and colors requires synesthetes first to identify the members of the inducers, and second, being able to understand the intuitive meaning of such series, hence the synesthetic association is then possible to be constructed within one’s mind. (Rouw et al., 2017)

4.2 Acoustic

The acoustic property is another inducer that exemplifies the role of learning in grapheme-color synesthesia. According to earlier studies, it is proposed that synesthetes from diverse linguistic backgrounds exhibit consistent connections between vowel sounds and their corresponding colors. (Marks, 1975)

Guillamón (2014) explored the connections between specific sounds and colors in non-synesthetes across various languages. The study revealed that specific properties of vowel sounds correspond to particular colors; for instance, the front-mid spectrum is linked to green. Notably, the front-open spectrum, which includes the /a/ or /a/ sounds, was associated with red in several languages: Japanese (Miyahara, Amemiya, & Sekiguchi, 2006), Polish and English (Wrembel, 2007), and Arabic (Guillamón, 2014). Further research by Kim, Nam, & Kim (in press) demonstrated that low vowels like lal are connected to more reddish hues in non-synesthetes when the synesthetic vowel sounds were adjusted based on tongue body position.

Similar to the semantic property, the acoustic property is

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generally associated with the learning process because the concurrent-inducer association can only be formed after the synesthetes can correctly identify and pronounce these graphemes and words. The ability to read and pronounce does not come naturally but is acquired by learning, thus emphasizing the importance of learning in forming an acoustic synesthetic experience.

4.3 Ordinal

Ordinal position may influence color perception primarily for notable positions, such as the first or last grapheme in an alphabet. Rouw et al. (2014) found that the first grapheme is typically red among synesthetes and non-synesthetes with American, Hindi or Dutch background. Additionally, Monday—the first day of the workweek in these cultures—was also linked to the color red by calendar-color synesthetes and non-synesthetes alike. This suggests a strong association between the concept of "first" and the color red.

Eagleman (2013) observed that letters at the beginning of the alphabet are linked to distinct colors. In contrast, those at the end tend to share similar hues, indicating a secondary relationship between ordinal position and color uniqueness. Asano and Yokosawa (2013), using second-order similarity mappings akin to those employed by Watson et al. (2012), investigated the factors influencing synesthetic colors in Hiragana, a Japanese phonetic script. They found that differences in ordinality (the sequence position of graphemes) were the strongest predictors of color distance (including luminance, saturation, and hue distance). Phonological similarity was the next most significant factor, while visual shape similarity and familiarity with the graphemes had the weakest influence.

Rich (2004) investigates the relationship between the ordinal features in the graphemes-color synesthetic relationships and learning experiences. Research states that elements of standard sequences, such as letters, numbers, days of the week, and months of the year, often trigger synesthesia. In the study, synesthetes who perceived colors for a limited range of lexical stimuli typically did so for days of the week, letters, and digits rather than for categories like animal names. This indicates that stimuli learned within conventional sequences might be crucial in forming synesthetic inducer-color associations.

4.4 Visual

Visual features of the graphemes can induce first-order inducer-concurrent relationships in grapheme-color synesthesia. Hubbard and Ramachandran (2005) initially suggested that synesthetes might link letters with curved versus sharp features to "warm" versus "cool" colors, although this observation was not quantified. Spector and Maurer (2011) suggest that common inducer-concurrent relationship between the letters "O" and white and "X" and "Z" with black stem from the propensity of associating smooth shapes with white and jagged shapes with black. To eliminate potential semantic association confounds, they assessed this effect's strength in non-synesthetic, pre-literate children, demonstrating that these children still significantly associate "O" with white and "X" and "Z" with black more often.

5. Cognitive Mechanisms Underpinning Learned Associations

Understanding the cognitive processes that generate learned associations in grapheme-color synesthesia requires the examination of memory, attention, and perception.

Memory plays a crucial role in establishing and maintaining synesthetic associations. Meier and Rothen (2009) proposed that synesthetic pairings result from associative learning mechanisms akin to those involved in classical conditioning. Repeated co-occurrence of graphemes and colors strengthens these associations, making them automatic and enduring.

Attention modulates the strength and consistency of synesthetic experiences. Ward et al. (2007) found that synesthetes exhibited enhanced attentional binding between graphemes and colors, suggesting that focused attention reinforces these associations. Additionally, interference tasks disrupting attentional focus weakened synesthetic perceptions, highlighting the interplay between attention and learned associations.

6. Conclusions

Although good progress is made in understanding the impact of learning in grapheme-color synesthesia, several challenges still lie in the way, and tackling these will require teamwork across different fields and new creative methods. One big challenge today is to explain the individual variability among different synesthetes, as synesthetic experiences vary from person to person. Even though there are some common patterns based on semantic, acoustic, visual, or ordinal features of graphemes, each synesthete's experience is still unique in a general perspective when considering all graphemes together. This may be due to their own cultural and language background as well as learning environment. Hence, future research should try to find out what causes these differences and work on designing models for how synesthesia develops.

Despite of exploring the variance among individual synesthetes, conducting long-term studies to observe synesthetes from childhood to adulthood are also critical for understanding the variation of these concurrent-inducer relationships over time. Research in this aspect is still limited for studying the consistency of the grapheme-color pairings. As a result, more future implications are demanded to uncover the key periods for synesthetic development, as well as the key factors for molding synesthetic associations, thus, investigating how these experiences grow and change.

Advances in brain imaging and computational modeling can be crucial in studying the neurological underpinnings of grapheme-color synesthesia. High-resolution imaging is helpful for seeing intricate details of brain connections, while machine learning can sift through complex data to uncover patterns in synesthetic associations.

In summary, this literature review provides an insight into how learning influences the formation and growth of grapheme-color synesthesia, taking into account various developmental, cultural, and cognitive factors. Early experiences and learned associations are of significance in shaping and sustaining synesthetic perceptions. This intricate relationship between learning and synesthesia has significant implications in various aspects such as education, cognitive science, and neuroscience. By tackling current challenges and exploring new direction of research, we can deepen our understanding of synesthesia's complexities and enhance our overall grasp of human cognition as well as the workings of the mind.

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