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LIST OF PAPERS

This thesis has been written in a format to satisfy requirements from both Aalborg University (for which full papers were included as annexes) and the University of Chinese Academy of Science (which does not allow for annexes). The chapters of the thesis are based on the following papers:

Chapter 4.
Zelazny, A., Liu, X., & Sørensen, T. A. (2023). Shape–color associations in an unrestricted color choice paradigm. Frontiers in Psychology, 14, 1129903. doi.org/10.3389/fpsyg.2023.1129903

Chapter 5 and 6.
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ENGLISH SUMMARY

While synesthesia is a rare phenomenon estimated to occur in about 4% of the population, its counterpart - cross-modal correspondence - occurs in the majority of the population. Synesthesia distinguishes itself from cross-modal correspondence by being a conscious and idiosyncratic experience. In the case of grapheme-color synesthesia, the most commonly reported type of synesthesia, individuals automatically and perceptually experience a specific color upon viewing a given grapheme. A variety of tasks have been designed to sample those experiences and understand their mechanisms.

Researchers have made use of those automatic and perceptual aspects and designed a synesthesia version of the Stroop task. A congruency effect was found in synesthetes in the ink-naming task, a task where participants are asked to name the color of the stimulus displayed, ignoring their synesthetic experience. Non-synesthete adults have also been tested on this task after having received a training in order to develop synesthesia. A congruency effect was found post-training in the ink-naming task, and its reverse task, called the retrieval task, in which participants have to name the trained association, ignoring the displayed stimulus' color. Furthermore, the ink-naming and retrieval tasks of the synesthesia Stroop have been found to give opposite patterns of results when testing synesthetes who experience their color internally or externally. Commonly, the response times and congruency effects found in the various tasks of the synesthesia Stroop are used as indirect measures of synesthetic or synesthesia-like experiences at the group level.

While synesthesia is a conscious experience, cross-modal correspondence is an unconscious one, meaning that when asking individuals to report intuitive associations, a group analysis is carried out to extract specific patterns of, for example, stimulus-color associations. Synesthetic associations have long been established as highly idiosyncratic, when cross-modal correspondence, on the other hand, by its universal aspect, implies low idiosyncrasy. Therefore, much focus has been put on unveiling the hypothesized one-to-one stimulus-color associations existing in the general population, in the case of color-related cross-modal correspondences.

This thesis presents three studies which aim to replicate previous results and evaluates whether their methodological decisions may have overestimated the non-idiosyncratic aspect of cross-modal correspondences and the meaning of congruency effects in the synesthesia Stroop. Chapter 1 is a short introduction to the topic of this thesis. Chapter 2 provides an overview of the various hypotheses regarding the origin and neuro-mechanisms of synesthesia. Chapter 3 presents the most common overt and indirect methods that have been used to assess the presence of synesthesia and cross-modal correspondence in individuals. Chapter 4 presents a study carried out on 7,517 Danish individuals using an overt report method to assess the degree of idiosyncrasy in shape-color cross-modal correspondence. The study presented in Chapter 5 aimed to evaluate whether the retrieval task of the synesthesia Stroop truly taps into the mechanisms of internally experienced synesthesia. Chapter 6 details a study attempting to replicate congruency effects in the ink-naming task of the synesthesia Stroop in the absence of any synesthetic experience, in order to highlight possible linguistic confounds. Conclusions are discussed in Chapter 7.

Overall, the three studies presented indicate that, first, shape-color correspondences may not be as non-idiosyncratic as commonly assumed. Previous studies investigating shape-color associations may have artificially resulted in one-to-one pairings due to methodological decisions. Second, while the ink-naming task of the synesthesia Stroop provides congruency effects due to synesthetic experiences, even internal ones, the retrieval task can lead to congruency effects in the absence of any synesthetic experiences, or even when the congruency conditions clash with the synesthetic experiences. Third, congruency effects in the ink-naming task should nevertheless not be taken as absolute proof of a synesthetic experience, as they can be emulated simply by relying on orthographic cueing.

In summary, the three studies presented here show that methodological decisions can lead to performances similar to synesthesia in the absence of any perceptual synesthetic experiences and also artificially exaggerate differences between synesthesia and cross-modal correspondence.

DANSK RESUME

Selvom synæstesi er et sjældent fænomen, forekommer dets modstykke, tværmodal korrespondance (i.e., cross-modal correspondence), hos størstedelen af befolkningen. Synæstesi adskiller sig fra tværmodal korrespondance ved at være en bevidst og idiosynkratisk oplevelse, som skønnes at forekomme hos ca. 4 % af befolkningen. Ved grafem-farve-synæstesi, der er den mest almindeligt rapporterede form for synæstesi, får personer en automatisk og perceptuel oplevelse af en bestemt farve, når de ser et givet grafem. Der er blevet udformet en række forskellige opgaver for at undersøge disse oplevelser og forstå deres mekanismer.

Forskere har gjort brug af disse automatiske og perceptuelle aspekter og udformet en synæstesi-version af Stroop-opgaven (i.e., Stroop task). Der blev fundet en kongruens effekt (i.e., congruency effect) hos synæstetikere i blæk-benævnelsesopgaven (i.e., ink-naming task), hvor deltagerne bliver bedt om at nævne farven på den viste stimulus uden at tage hensyn til deres synæstetiske oplevelse. Denne opgave er også blevet udført på voksne ikke-synæstesikere, som var blevet trænet med henblik på at erhverve synæstesi. Her blev der fundet en kongruens effekt efter træning i blæk-benævnelsesopgaven og dens omvendte opgave, den såkaldte genkaldelsesopgave (i.e., retrieval task), hvor deltagerne skal nævne den trænede associerede farve uden at tage hensyn til den viste stimulus' farve. Desuden har det vist sig, at blæk-benævnelsesopgaverne og genkaldelsesopgaverne i synæstesi Stroop giver modsatte resultatmønstre, når man tester synæstetikere, der oplever deres farve internt eller eksternt. Almindeligvis anvendes de responstider og kongruens effekter, der findes i de forskellige opgaver i synæstesi Stroop, som indirekte mål for synæstesi eller synæstesi-lignende oplevelser på gruppeniveau.

Mens synæstesi er en bevidst oplevelse, er tværmodal korrespondance en ubevidst oplevelse, hvilket betyder, at når man beder personer om at rapportere intuitive associationer, foretages der en analyse på gruppeniveau for at uddrage specifikke mønstre af f.eks. stimulus-farveassociationer. Synæstetiske associationer er længe blevet set som idiosynkratiske, mens tværmodal korrespondance på den anden side bliver set som universelt, og dermed indebærer en lav grad af idiosynkrasi. Derfor har der været meget fokus på at afdække de antagede en-til-en stimulus-farveassociationer, der findes i den generelle befolkning, når det vedrører farve-relaterede tværmodale korrespondancer.

Denne afhandling præsenterer tre studier, som har til formål at genskabe tidligere resultater, samt at evaluere, om metodologiske beslutninger kan have medvirket til en overvurdering af det ikke-idiosynkratiske aspekt af tværmodale korrespondancer og betydningen af kongruens effekter i synæstesi Stroop-opgaven. Kapitel 1 er en kort introduktion til emnet for denne afhandling. Kapitel 2 giver en oversigt over de forskellige hypoteser vedrørende synæstesiens oprindelse og de bagvedliggende neurale mekanismer. I kapitel 3 præsenteres de mest almindelige direkte og indirekte metoder, der er blevet anvendt til at vurdere tilstedeværelsen af synæstesi og tværmodale korrespondancer hos enkeltpersoner. Kapitel 4 præsenterer en undersøgelse, der er udført på 7517 danske personer, og som anvender en direkte rapporteringsmetode til at vurdere graden af idiosynkrasi i form-farve tværmodal korrespondance. Undersøgelsen, der præsenteres i kapitel 5, havde til formål at bekræfte, om genkaldelsesopgaven i synæstesi Stroop virkelig er et udtryk for mekanismerne for internt oplevet synæstesi. Kapitel 6 beskriver en undersøgelse, der forsøgte at genskabe kongruenseffekterne i blæk-benævnelsesopgaven i synæstesi Stroop i personer uden synæstetisk erfaring med henblik på at fremhæve mulige sproglige fejlkilder. Konklusionerne diskuteres i kapitel 7.

Samlet set viser de tre studier, der præsenteres nedenfor, for det første at form-farveassociationer muligvis er mere idiosynkratisk end der normaltvist antages. Tidligere studier, der undersøger form-farveassociationer, kan kunstigt have resulteret i en-til-en-parringer på grund af metodologiske beslutninger. For det andet viser studierne, at mens blæk-benævnelsesopgaven i synæstesi Stroop giver kongruens effekter på baggrund af synæstetiske erfaringer, selv interne, kan genkaldelsesopgaven føre til kongruens effekter i fravær af synæstetiske erfaringer, eller endda når kongruensbetingelserne ikke stemmer overens med de synæstetiske erfaringer. For det tredje bør kongruens effekter i blæk-benævnelsens opgaven ikke tages som et absolut bevis på en synæstetisk oplevelse, da de kan efterlignes ved blot at stole på ortografisk cueing (i.e., orthographic cueing).

I forlængelse heraf viser de tre studier, der er præsenteret her, at metodologiske beslutninger både kan føre til præstationer, der ligner synæstesi, i fraværet af perceptuelle synæstetiske oplevelser, samt kunstigt overdrive forskellene mellem synæstesi og tværmodal korrespondance.

中文摘要

虽然联觉(synesthesia)是一种罕见的现象，但它的对应物(counterpart)——跨通道对应(cross-modal correspondence)会在大多数人身上发生。前人设计了各种各样的任务来对这些行为进行采样，并试图了解它们的机制。联觉与跨通道对应的区别在于，它是一种有意识的、特殊的体验，发生在大约4%的人口中。最常见的联觉是字形-颜色联觉，即人们在看到一个给定的字形时，会自动地、感知性地体验到特定的颜色。

因此，本研究利用这些自动与知觉层面，设计了一个Stroop任务的联觉版本。在颜色命名任务(ink-naming task）中，联觉实验参与者被要求说出所显示的刺激的颜色，忽略他们的联觉经验。我们在联觉者身上发现了一致性效应(congruency effect）。这项任务也在没有联觉的成年人身上进行，他们在任务之前接受了旨在获得联觉的练习。在训练后，在颜色命名任务和与之相反的，被称为检索任务的两个任务中，我们发现了一致性效应。这检索任务中，实验参与者必须说出被训练的联想，而忽略显示刺激的颜色。此外，当测试内部或外部体验颜色的联觉者时，Stroop联觉的颜色命名和检索任务中发现了相反的结果模式。通常，在联觉Stroop的各种任务中发现的反应时和一致性效应被用作组水平上的联觉或类联觉经验的间接测量。

虽然联觉是一种有意识的体验，但跨模态对应是一种无意识的体验，这意味着当要求研究参与者报告直觉性的联结时，进行组分析可以提取特定的模式，如刺激-颜色关联。长期以来，联觉联结一直被认为是特质性的，而另一方面，跨通道对应由于其普遍方面，意味着低特质性。因此，在与颜色相关的跨通道对应的情况下，许多重点被放在揭示一般人群中存在的假设的一对一刺激-颜色关联上。

本论文介绍了三个研究，旨在重复前人的结果，以及评估方法选用是否可能高估了跨通道对应的非特质方面和Stroop联觉中一致性效应的意义。第1章是对本文主题的简要引言部分。第2章概述了关于联觉起源和神经机制的各种假设。第3章介绍了用于评估个体中联觉和跨模态对应的存在的最常见的外显和间

接方法。第4章介绍了一项对7517**名丹麦人**进行的研究，使用外显报告方法评估形状-颜色跨通对应的特质程度。第5**章提出的研究旨在确**认Stroop联觉的检索任务是否真正利用了内部体验联觉的机制。第6**章**详细介绍了一项研究，试图在没有任何联觉经验的情况下，在Stroop联觉的颜色命名任务中复制一致性效应，以突出可能的语意混淆。结论将在第7**章**讨论。

总的来说，下面提出的三项研究表明，首先，形状-颜色关联可能不像通常假设的那样非特质。前人研究中形状-颜色关联的研究可能是由于方法上的选用而人为地导致了一对一的配对。其次，由于联觉经验，甚至是内在的联觉经验，联觉Stroop**的**颜色命名任务中都出现了一致性效应，而在没有任何联觉经验的情况下，甚至当一致性条件与联觉经验冲突时，检索任务也会导致一致性效应。第三，颜色命名任务中的一致性效应不应被视为联觉经验的绝对证据，因为它们可以简单地依靠正**字法**线索(orthographic cueing)**来模**拟。

不断地，本论文提出的三个研究表明，在没有任何知觉联觉经验的情况下，方法上的选用既可以导致与联觉相似的表现，也可以人为地夸大联觉和跨通道对应之间的差异。

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TABLE OF CONTENTS

TABLE OF FIGURES

CHAPTER 1. INTRODUCTION

"Black A, white E, red I, green U, blue O", this is how Rimbaud (1883) began one of his most famous poems. While many would ponder about the meaning of this line, others would be met with confusion, as they clearly know that A is not black, E is not white, I is not red, U is not green and O is not blue! How do they know this? Simply because as they read the poem, they do not see a string of black letters. Instead, they see each letter colored, as clearly as we can see that the sky is blue just by looking out the window.

Perceptually and involuntarily experiencing a color in response to a stimulus deprived of color information is one of the many types of synesthesia that have been reported. Although a large variety of sensory modalities can be involved, graphemes having colors is one of the most common types of synesthesia experienced (Day, 2005).

Scientists have long tried to understand the phenomenon of synesthesia, a neurological phenomenon in which experiencing a certain set of stimuli leads to an experience in an unrelated sensory modality. Its involuntary and automatic aspects have been described as early as in 1772 (Herder, 1772; Jewanski et al., 2020). With time, other characteristics were unveiled, including its consistency over time, idiosyncrasy, and arbitrariness (Grossenbacher & Lovelace, 2001; Simner, 2012; Ward, 2013).

In the last couple of decades, researchers have developed a variety of methods to assess the phenomenon of synesthesia, to demonstrate its genuineness, and to understand its mechanisms (e.g., Dixon et al., 2000; Eagleman et al., 2007). At the same time, mounting evidence suggests that non-perceptual associations between modalities also exist in the general population (Spence, 2011), where for example high pitches are associated to bright colors (Marks, 1974). This phenomenon is currently called cross-modal correspondence.

While the term synesthesia came to define the unusual experiences occurring in a small portion of the population, the term cross-modal correspondence designates a phenomenon experienced by virtually the entire population. Cross-modal correspondence and synesthetic experiences are proposed to differ on several accounts and the conscious and prevalence aspects have been argued to be the main factors differentiating the two phenomena (Deroy & Spence, 2013). Cross-modal correspondence is hypothesized to be universal, meaning that the majority of the population experience the same associations, involving therefore low idiosyncrasy (Spence, 2011). Cross-modal correspondence has also been defined as unconscious (Spence, 2011), meaning that in the case of pitch-brightness cross-modal correspondence, while individuals will show a bias towards associating high pitches to bright colors, they do not *see* bright colors upon hearing a high pitch. Synesthesia on the other hand occurs in only few individuals and is conscious, meaning that sound-color synesthetes will *see* colors upon hearing certain sounds. Furthermore, despite the fact that some general patterns of associations also exists in synesthesia (e.g., over

30% of synesthetes perceive the letter B in blue; Day, 2004; Rich et al., 2005; Simner et al., 2005), the arbitrariness of the synesthetic associations leads to strong idiosyncrasy (Grossenbacher & Lovelace, 2001).

The present thesis presents three studies which evaluate how methodological decisions may have, on the one hand, artificially exaggerated the universal and low idiosyncratic aspects of cross-modal correspondences (specifically, shape-color associations; Chapter 4), and on the other hand overlooked mechanisms (Chapter 5) and confounders (Chapter 6) that may have led to similar results between non-synesthetes trained to acquire synesthesia and genuine synesthetes, failing therefore to tap into specific aspects of synesthesia.

CHAPTER 2. SYNESTHESIA

2.1. PRESENTATION OF SYNESTHESIA

2.1.1. DESCRIPTION AND PREVALENCE

Color perception begins with certain waves of light entering the eye. As they reach the retina, photoreceptor cells get activated, sending a signal which travels through the optical nerve, to reach the occipital cortex, where it is processed by the V4/V8 areas (Bartels & Zeki, 2000; Zeki & Marini, 1998). This process leads to a perceptual color experience. In color-related synesthesia however, color perception does not occur exclusively due to light wave stimulus (Cytowič, 2002a; Hubbard, Arman, et al., 2005). Instead, it can be due to sound waves (e.g., sound-color synesthesia), chemical molecules (e.g., smell-color synesthesia) or pressure (e.g., touch-color synesthesia) (Robertson & Sagiv, 2004). In short, in color-related synesthesia, a synesthetes sees color in the absence of colored stimuli.

Synesthesia is commonly defined as a neurological phenomenon in which experiences in one sensory modality lead to automatic experiences in an otherwise unrelated modality. The sensation that triggers the synesthesia is called “inducer”, while the subsequent sensation is called the “concurrent” (Grossenbacher & Lovelace, 2001). Although the examples of synesthesia cited previously all involve the visual modality as concurrent, all modalities can be involved such as touch (e.g., sound-touch synesthesia) or taste (e.g., sound-taste synesthesia). Over 70 different types of synesthesia have been reported so far (Day, 2005; 2022). While some types of synesthesia tend to co-occur more than others (Novich et al., 2011; Ward & Simner, 2022), all types of synesthesia are still thought to be the manifestation of the same phenomenon. It is nevertheless difficult to establish an exhaustive list of all types of synesthesia, as those rely on spontaneous reports from individuals. This is exacerbated by the fact that some types of synesthesia are less prevalent than others. While synesthesia was originally estimated to occur in one in 25,000 to 100,000 individuals (Cytowič, 1993; 1997), an empirical study using random sampling of the population has shown that synesthesia might rather occur in 4% of individuals (Simner et al., 2006). Grapheme-color synesthesia is the far most often studied type, but its prevalence is still subject to questioning, as some studies report a prevalence of up to 68.8% of synesthetes (Day, 2005), while others are more conservative and report grapheme-color synesthesia in only about 30% of synesthetes (Simner et al., 2006). At the same time, grapheme-color synesthesia is estimated to occur in 1% to 1.4% of the general population (Carmichael et al., 2015; Simner et al., 2006; 2009; Simner & Carmichael, 2015). Other common types of synesthesia include weekday-color (where days of the week have a color; Day, 2005; Simner et al., 2006), time-space (where people perceive time units, such as weekdays, as having a position in space;

Day, 2005) and music-color synesthesia (Day, 2005). Music-color synesthesia includes color responses to all aspects of music (melody, rhythm, instruments, chords, notes, voice, texture, etc.). Examples of more rare types of synesthesia are lexical-gustatory synesthesia (Jones et al., 2011; Simner & Haywood, 2009; Simner & Logie, 2008; Ward & Simner, 2003), where words trigger a taste sensation (estimated in 1.9% of synesthetes; Day, 2005) or ticker-tape synesthesia (Chun & Hupé, 2013; Holm et al., 2015), where individuals see words written in front of them as they hear them being spoken.

Synesthesia has long been thought to show a gender bias in favor of women, being six times more common in women than men (Barnett, Finucane, et al., 2008; Baron-Cohen et al., 1996; Rich et al., 2005). However, random sampling of the population (Simner et al., 2006; Simner & Carmichael, 2015) indicated that such a bias is probably due to women being more likely to voluntarily report their experiences (Simner & Carmichael, 2015), with the actual distributions between men and women being equal.

Finally, a central characteristic of synesthesia resides in the fact that associations are consistent over time (Baron-Cohen et al., 1993; Cytowič, 2002b) and idiosyncratic (Barnett, Finucane, et al., 2008; Grossenbacher & Lovelace, 2001), meaning that while some commonalities occur when looking at individual grapheme-color pairs (e.g., over 40% of synesthetes report that the letter A is red; Day, 2004; Rich et al., 2005; Simner et al., 2005) two grapheme-color synesthetes are likely to have different colors for a full set of graphemes (see Fig. 2-1, taken from Zelazny & Sørensen (2022), for an illustration of the consistency over time and idiosyncrasy of synesthesia).

2.1.2. DIFFERENT CLASSIFICATIONS OF SYNESTHESIA

Efforts to understand the mechanisms of synesthesia have involved attempts to classify synesthesia into different categories. Different classification criteria have therefore been put forward based on the phenomenological aspects of the synesthetic experiences.

Regardless of their types of synesthesia, synesthetes are commonly divided between "projectors" and "associators" (Dixon et al., 2004). While associators experience the concurrent internally (meaning in their "mind's eye"), projectors experience the concurrent externally, as projected onto their environment. Grapheme-color associators would therefore perceive colors upon seeing graphemes in their "mind's eye", whereas for grapheme-color projectors, the color is perceived on top or around the inducer grapheme. Only 10 to 15% of grapheme-color synesthetes are estimated to be projectors (Dixon et al., 2004; Dixon & Smilek, 2005; Ramachandran et al., 2020). In the case of grapheme-color synesthesia, projector and associator synesthetes have been further divided into four groups: "surface-projectors" who experience the concurrent color on top of the inducer, "space-projectors" who experience the color in an external space nearby the inducer, “see-associators” who perceive the concurrent color in their mind’s eye and “know-associators” who only have a strong knowledge of a color identity when perceiving a grapheme (Ward et al., 2007).

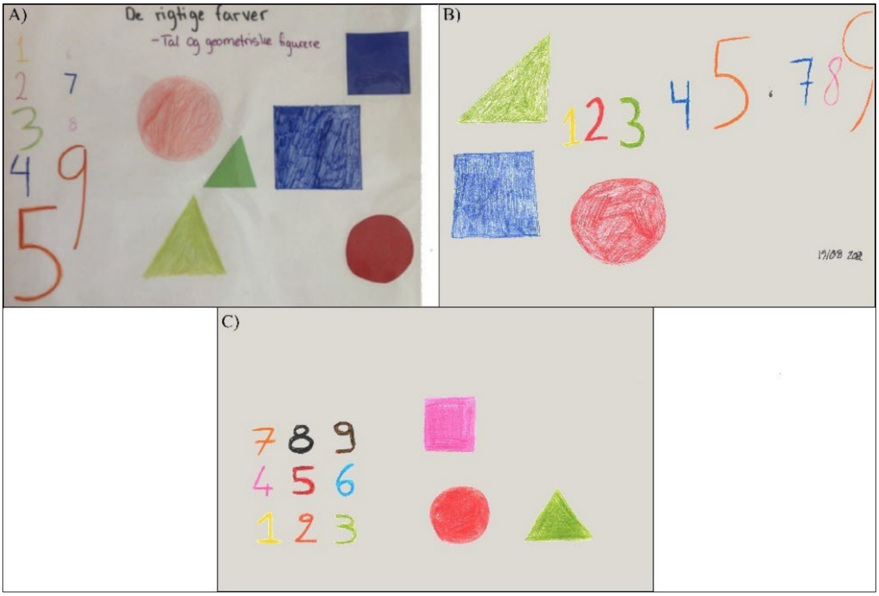

Figure 2-1. Illustrations of synesthetic associations for digits and shapes in two synesthetes. (A) Drawing from synesthete AR, made in 2013, titled “the correct colors - numbers and geometrical shapes”. The drawing shows the color and size perceived for each digit and the perceived color of each shape. (B) Another drawing by synesthete AR in 2020, seven years later, where we can see the colors and sizes are identical. (C) Drawing made by synesthete AZ in 2020 of her shape-color and digit-color synesthesia, which differ from AR’s.

Synesthesia has also been classified into different subgroups, depending on the nature of the inducer. Day (2005) labeled as “synesthesia proper” synesthetic experiences that are due to perceptual information, such as smells, sounds or sights. “Category synesthesia” on the other hand designates abstract concept inducers, which are typically acquired through culture, such as graphemes, time units or music notes. A few years earlier (Grossenbacher & Lovelace, 2001), synesthetic experiences had already been distinguished based on whether they were due to actual perceptual experiences (called “synesthetic perception”) or due to thinking of a certain concept (called “synesthetic conception”). These distinctions operate at the level of the synesthesia type itself (e.g., time unit-color is a case of synesthetic conception/category synesthesia, while touch-color is a case of synesthetic perception/synesthesia proper), and the categorization does not depend on the synesthete’s experience.

However, a type of perceptual/conceptual distinction has been defined at the individual level for every type of synesthesia. Individuals who experience a concurrent as a result of sensorily perceiving an inducer (e.g., seeing the grapheme

"A") have been labeled "lower synesthetes", while those who experience a concurrent due to merely thinking about the inducer (e.g., thinking about the grapheme "A") were called "higher synesthetes" (Ramachandran & Hubbard, 2001b). As such, grapheme-color synesthesia can be a case of lower synesthesia in an individual who experiences color only upon seeing a grapheme, whereas it would be classified as higher synesthesia for an individual who experiences colors upon thinking about a given grapheme.

The relationship between inducer and concurrent also gave rise to a different classification of types of synesthesia. Marks & Odgaard (2005) called for a distinction between intramodal and intermodal (or cross-modal) types of synesthesia. The intramodal types of synesthesia have concurrents and inducers that are different types of information belonging to the same sensory modality. For example, grapheme-color synesthesia deals with graphemes and colors, which are both visual information. Intermodal types of synesthesia, on the other hand, span over different modalities, such as odor-color synesthesia, which starts in the olfactory modality and gets converted into visual information. Interestingly, why synesthesia is commonly defined as a link between sensory modalities, its most prevalent type, namely grapheme-color synesthesia, involves a single modality, as both graphemes and colors belong to the visual modality. Marks & Odgaard (2005) argued that nonetheless, different dimensions of the visual modalities are involved in grapheme-color synesthesia. Furthermore, while shape stimuli (e.g., graphemes) often hold a color information, they are not dimensions of the visual modality that are dependent of each other, as shape and color information can be processed in isolation from each other (Marks & Odgaard, 2005). As such, perceiving a color when viewing a black grapheme denotes the involvement of a dimension of the visual modality that should normally not be involved. Marks & Odgaard (2005) pointed out, however, that intramodal and intermodal types of synesthesia can be differentiated, as the former involves dimensions that can naturally co-occur to form a single stimulus (e.g., a letter A written in pink), while the latter relies on dimensions of modalities that do not naturally co-occur in space and time (e.g., taste and color).

A last type of classification defines the conditions under which synesthetic experiences arise in an individual. Grossenbacher & Lovelace (2001) distinguish between three types of synesthesia. "Acquired synesthesia", which is a rare condition where synesthesia appears because of a brain injury in individuals who otherwise had not experienced this type of synesthesia before (Afra et al., 2009; Beauchamp & Ro, 2008; Fornazzari et al., 2012; Ro et al., 2007; Vike et al., 1984). In the case of abnormal mass growth in the brain, the synesthetic experience can be expected to disappear once the mass is removed (Vike et al., 1984). Acquired synesthesia has also been reported in cases of loss of sight (Armel & Ramachandran, 1999; Jacobs et al., 1981; Steven & Blakemore, 2004, see also Bolognini et al., 2013; Lessell & Cohen, 1979). "Pharmacological synesthesia" (also called drug-induced synesthesia), occurs as a result of drug ingestion. The experience appears 30 to 60 minutes after ingestion (depending on the type of drug) and begins to fade as the chemical agent causing the experience is cleared off the bloodstream of the individual's body (Luke & Terhune, 2013; Park et al., 2018; Sinke et al., 2012; Yanakieva et al., 2019). Finally, in "developmental synesthesia" (also called genuine synesthesia) individuals report experiencing the phenomenon since early childhood (Simner & Hubbard, 2013), without any action or event marking its start.

A reported case of loss of developmental synesthesia somewhat reintroduced using drugs (Mayer-Gross, 1931), as well as a more recent case of drug-induced long-lasting synesthesia (Yanakieva et al., 2019) nevertheless bring doubt on the impermeability of this classification of types of synesthesia.

Interactions between these various methods of classification also exist. Originally, the acquired and pharmacological types of synesthesia were defined as exclusively perceptual, involving inducers such as sounds (including music in pharmacological synesthesia), touch, taste, smell, and pain (Afra et al., 2009; Armel & Ramachandran, 1999; Sinke, Halpern, et al., 2012), as opposed to developmental synesthesia, which can be both perceptual and conceptual (Grossenbacher & Lovelace, 2001). However, later studies reported cases of conceptual synesthesia being acquired (Fornazzari et al., 2012) and subsequent to drug ingestion (Luke et al., 2022; Sinke et al., 2012), with inducers such as graphemes or ideas (Luke et al., 2022). Regarding concurrents, developmental synesthesia also shows a wider range of experiences, such as visuals (including "martian colors", meaning colors that cannot exist in the environment, such as greenish red; Ramachandran & Hubbard, 2001b), touch, space, taste, smell, and so on (Day, 2005, 2022). Acquired and pharmacological synesthesia however are mostly restricted to visual stimuli and touch (Sinke, Halpern, et al., 2012). An other difference resides in that acquired synesthesia is of the projector type (Jacobs et al., 1981), while pharmacological synesthetes can be both projectors or associators, depending on whether their eyes are open or closed (Sinke, Halpern, et al., 2012). Developmental synesthetes, on the other hand, can be either projectors or associators depending on the individual (Dixon et al., 2004).

Developmental synesthesia is also the only type where cognition has been found to be involved (Sinke, Halpern, et al., 2012), since developmental grapheme-color synesthetes are able to transfer their colors to new graphemes that share the same identity (Mroczko et al., 2009; Uno et al., 2020). In the case of acquired synesthesia, on the other hand, it is mainly the startling aspect of the sounds that causes the synesthetic experience, rather than its conceptual processing (Page et al., 1982).

Finally, while acquired, pharmacological, and developmental synesthesia all show high levels of idiosyncrasy (Sinke, Halpern, et al., 2012), only developmental synesthesia is highly consistent over time (Sinke, Halpern, et al., 2012) as well as automatic (Jacobs et al., 1981; Luke et al., 2022; Sinke, Halpern, et al., 2012).

The present thesis focuses exclusively on the developmental type of synesthesia.

2.2. ORIGINS OF SYNESTHESIA

In addition to describing the phenomenological aspects of synesthesia, much effort has been put into understanding its origins and mechanisms. Tentative accounts of synesthesia have been made at the genetic, neuroanatomical, cognitive, and environmental levels, yet no definite underlying mechanism has been demonstrated to date.

2.2.1. GENETIC EVIDENCE

By the end of the 19th century, the hereditary aspect of synesthesia had already been noticed (Galton, 1883). Over a century later, evidence emerged pointing to possible genetic links, with about one third of synesthetes having relatives with synesthesia (Baron-Cohen et al., 1996). The prevalence is even stronger in first-degree relatives, with 42-48.6% of them being synesthetes (Barnett, Finucane, et al., 2008; Baron-Cohen et al., 1996). It was also established that synesthesia is not passed on to the next generation through learning (i.e., parents teaching their associations to their children; Baron-Cohen et al., 1996), as the types of synesthesia, as well as the specific inducer-concurrent associations reported, differ between parents and children of same families.

The possible involvement of a single gene was proposed at first (Baron-Cohen et al., 1996). More precisely, it was argued that synesthesia is due to a gene on the X-chromosome, coupled with lethality in male fetuses (Baron-Cohen et al., 1996). The gender bias observed at the time supported this hypothesis. The male fetus lethality aspect was put forward as an account for the fact that synesthesia was thought to occur six times more often in women than men, but also to explain the observation that synesthete mothers have more daughters than sons (Baron-Cohen et al., 1996). However, using a larger sample of families, Ward and Simner (2005) found no difference in proportion of daughters and sons from synesthete mothers, imputing the lack of male offspring previously found to sample bias. They nevertheless reaffirmed the X-linked dominant mode of inheritance previously hypothesized, by which a parent transmitting a single allele of the mutated gene is enough to inherit the synesthesia trait. This account also allowed to explain the fact that no case of father-son transmission had ever been reported. Indeed, sons inherit their X-chromosome from their mother, therefore a synesthete father can only transmit his X-linked synesthesia gene to his daughters. However, this observation was refuted when two cases of father-son transmission of synesthesia were reported (Asher et al., 2009).

A case report of female monozygotic twins who showed discordant synesthesia profiles prompted the X-chromosome inactivation hypothesis (Smilek et al., 2002). One of the twins was a digit-color synesthete, while her sister did not report any type of synesthesia. Typically, in females, who feature two X-chromosomes, one of those X-chromosomes becomes inactive. The X-chromosome inactivation hypothesis therefore proposed that in the non-synesthete sister, the X-chromosome that held the synesthesia gene had been deactivated after the twinning process started. In the synesthete sister, on the other hand, it was the X-chromosome that did not carry the synesthesia gene that had been deactivated. A counter-example was however reported by the same researchers a few years later, where male monozygotic twins showed the same discordant synesthesia profiles (Smilek et al., 2005). In males, who only have one X-chromosome, no inactivation needs to occur, rendering their X-chromosomes identical, discrediting the X-chromosome inactivation hypothesis and casting doubt on the X-linked dominant mode of inheritance altogether.

In a whole-genome analysis, the chromosome 2q24 was found to be significantly linked to having sound-color synesthesia, and other chromosomes (i.e., 5q33, 6p12, and 12p12) showed a possible linkage as well (Asher et al., 2009). However, no linkage to the X chromosome was found. The single-gene proposal was henceforth abandoned. Genetic influences on synesthesia have been judged as more complex than previously thought and potentially not uniform in all individuals (Asher et al., 2009). Tomson and colleagues (2011) found a linkage to chromosomes 16q in sequence-color synesthetes. Having tested individuals with a different type of synesthesia than Asher and colleagues (2009) could be the reason for inconsistency between studies regarding the identified chromosomes, thus showing once again the heterogeneity of the genetic basis.

A whole-exome sequencing analysis performed in three families with sound–color synesthesia found variants in six genes. Although none of these variants were shared by all three families, the genes found seem to be associated with axonogenesis (Tilot et al., 2018). These identified genes were, however, not found in the chromosomes identified in previous genetic studies (Asher et al., 2009; Tomson et al., 2011).

Taken together, although evidence points to a role of genetics in synesthesia, a direct causal link is yet to be demonstrated. Rather, the presence of certain genes may instead increase the likelihood of having synesthesia, with other factors also playing a crucial role (Smilek et al., 2005; Tilot et al., 2018; Ward & Simner, 2005).

2.2.2. ARE WE ALL A LITTLE BIT SYNESTHETE?

Based on observations of maturing brains in mammals and human infants, Maurer (1993) hypothesized that all babies may be born synesthetes.

During the development of the human neocortex, a large number of connections between neurons are formed, called synaptogenesis. This process begins already before birth (Molliver et al., 1973) and slows down greatly in early childhood, with different brain regions following their own time course (Huttenlocher & Dabholkar, 1997). Normal brain development also requires a "pruning" process to occur, during which many synapses are eliminated (Chugani et al., 1987; Rabinowicz, 1986). Whether the synaptogenesis and pruning processes occur in parallel (Hua & Smith, 2004) or sequentially (Chugani et al., 1987; Rabinowicz, 1986) is not yet fully understood. Nevertheless, this pruning process is argued to follow Hebb's (1949) postulate and likely relies on experience-dependent plasticity (Chugani, 1994; Hua & Smith, 2004). In other words, sensory inputs dictate which neural connections are useful, and therefore get strengthened, and which ones are useless and are thus eliminated. This results in somewhat specialized sensory processing areas. However, this means that before the pruning process occurs, those brain areas are interconnected, resulting, for example, in speech causing activity in both the auditory and visual cortices of infants (Neville, 1995).

On this basis, Maurer (1993) proposed the Neonatal Hypothesis of synesthesia, according to which all babies are born synesthetes. The fact that only some adults remain synesthetes would be due to a combination of abnormal pruning during the first years of life, as well as a lack of inhibition of those connections that remained (Maurer, 1993; Maurer et al., 2013; Spector & Maurer, 2009). Indeed, the Neonatal Hypothesis also accounts for the fact that non-synesthetes show associations across modalities, called cross-modal correspondence, where for example high-pitched sounds evoke bright lights (Marks, 1987). In non-synesthete adults, some early connections may have remained, but those become inhibited (Maurer, 1993; Maurer et al., 2013; Spector & Maurer, 2009), resulting in those cross-modal associations being a “muted form” of synesthesia (Spector & Maurer, 2009).

Extensive literature on the cross-modal associations in non-synesthetes referred to by Spector and Maurer (2009) exists (see Spence (2011) for a review). While most are dedicated to auditory-visual associations, a large variety of associations have also been investigated, including vision-touch (Martino & Marks, 2000; Spence, 2002), smell-touch (Demattè, Sanabria, Sugarman, et al., 2006), smell-color (Demattè, Sanabria, & Spence, 2006; Gilbert et al., 1996) or sound-taste (Knöferle & Spence, 2012), showing that cross-modal correspondence can be as varied as synesthesia.

Cross-modal correspondence differs, however, from synesthesia by its lack of idiosyncrasy and the fact that it does not cause any conscious perception (Deroy & Spence, 2013). In fact, while two synesthetes may experience completely different concurrents for a given inducer (see Fig. 2-1), cross-modal correspondence is argued to be largely shared by the whole population (Deroy & Spence, 2013).

Spence (2011) proposed that cross-modal correspondence can be divided into three types based on the hypothesized underlying mechanism. The first type is “structural correspondence”, which may be due to the brain’s intrinsic way of coding sensory information. For example, loudness may be mapped into brightness (Marks, 1978), due to the neural firing in response to loudness intensity relying on a same mechanism as the neural firing encoding brightness intensity (Spence, 2011; Stevens, 1957). The second is “statistical correspondence”, which are associations that are learned through interactions with the environment. In the case of sound-motion associations (Teramoto et al., 2010), having repeatedly experienced the decreasing sound of cars driving away have taught us that noise faints as the object causing it moves away from us. Finally, the last one is “semantic correspondence”, which might be derived from language. The most common example is pitch-elevation associations, where “high” and “low” are common attributes of pitch in most languages (Spence, 2011; Stumpf, 1890). In Farsi and Turkish on the other hand, pitch is more commonly described in terms of thickness, leading Turkish and Farsi speakers to show pitch-thickness associations, rather than pitch-elevation ones (Dolscheid et al., 2020; Judith Holler et al., 2022). Later, a forth category of cross-modal correspondence was defined as "hedonic correspondence" (Malfatti, 2014; Spence, 2022), which are associations mediated by emotion. For example, happy music would be associated with happy colors (Palmer et al., 2013).

It has been argued that cross-modal correspondence reflects a spectrum of normal multisensory processing, where its most extreme forms are instances of synesthesia (Bien et al., 2012; Esterman et al., 2006; Martino & Marks, 2001; Mulvenna & Walsh, 2006). Martino and Marks (2001) defined cross-modal correspondence as "weak synesthesia" and developmental synesthesia as "strong synesthesia". Others have formulated that the existence of similar associations in both synesthetes and cross-modal correspondences indicates that synesthesia relies on mechanisms available from cross-modal correspondence (Eagleman, 2009; Mondloch & Maurer, 2004; Sagiv & Ward, 2006; Simner et al., 2005; Spector & Maurer, 2009). For example, both pitch-color synesthetes and non-synesthetes show the associations for pitch and lightness (Ward, Huckstep, et al., 2006), where low pitches are dark and high pitches bright. Synesthetes however would associate a highly specific color to each pitch, whereas non-synesthetes do not show such consistency (Ward, Huckstep, et al., 2006). Deroy and Spence (2013) pointed out though that such accounts may be biased due to overly relying on similarities between the two phenomena and overlooking the key differences. One of those dissimilarities is the obvious lack of conscious experience in cross-modal correspondence, but its lack of idiosyncrasy also puts in question whether synesthesia is truly just a mere conscious experience of cross-modal correspondence. As a result of this idiosyncrasy, synesthetic associations appear highly arbitrary, which is not the case for cross-modal correspondence (Brang & Ramachandran, 2020). Spence (2011) classified cross-modal correspondences as structural, statistic, semantic, or hedonic in nature in order to also provide some explanation regarding their underlying mechanisms and rationales. As such, the mapping of pitch height into brightness falls under the category of structural cross-modal correspondence, as the association is hypothesized to be due to similar neural mechanisms to represent intensity (i.e., high pitch intensity mapped into high brightness intensity) across modalities (Spence, 2011). For this reason, associations between low pitch intensity and high brightness intensity should be unexpected. Opposingly, no such expectations have been formulated for synesthetic associations. For example, referring to Fig. 2-1, synesthete AR's "7-blue" association is not more or less expected than synesthete AZ's "7-orange" association.

2.2.3. NEUROANATOMICAL HYPOTHESES

Behavioral, EEG, MEG and fMRI data have pushed researchers to formulate hypotheses regarding the underlying neural mechanisms of synesthesia. Indeed, different brain activations and behavioral performances seem to indicate that synesthetes and non-synesthetes feature distinct neural properties. Hyperconnectivity due to failed pruning and disinhibition was already hypothesized by the Neonatal Hypothesis of synesthesia (Maurer, 1993). This idea was further developed in the following decade, resulting in more or less competing models. Bargary and Mitchell (2008) have sorted those neural models of synesthesia according to whether they implicate direct or indirect cross-activation between inducer and concurrent brain areas, and whether they rely on structural or functional differences with the non-synesthetic brain.

Ramachandran and Hubbard (2001a) hypothesized that a direct cross-activation between the color area V4 and the number area was at the origin of the experience of digit-color synesthetes. Both areas are part of the fusiform gyrus (Pesenti et al., 2000; Rickard et al., 2000), which is argued to be the reason why grapheme-color synesthesia is so prevalent (Hubbard & Ramachandran, 2005; Ramachandran & Hubbard, 2001a). This Cross-Activation Theory was later extended to other types of synesthesia, which also involve adjacent brain areas (Hubbard et al., 2011), including number-form synesthesia (i.e., ordinal sequences such as numbers, letters or time units being perceived in space), music-taste synesthesia or word-taste synesthesia. They nevertheless pointed out that some types of synesthesia, such as tone-color synesthesia, do not implicate adjacent brain areas.

The Cross-Activation Theory was updated a decade later in the light of data showing involvement of the parietal lobe as the site of color–grapheme binding (Esterman et al., 2006), resulting in the Cascaded Cross-Tuning model (Hubbard et al., 2011). Synesthesia was therefore modeled as a two-step process, involving first cross-activation of sensory areas, where grapheme features activate different possible color experiences until top-down processes give rise to a single grapheme and color pairing, followed by a binding of the inducer and concurrent in the parietal area.

While the Cross-Activation Theory postulates structural differences between the brains of synesthetes and non-synesthetes, others have argued that the differences may be more at the functional level. During sensory processing, bottom-up mechanisms suggest that information is transmitted from low-level to high-level processing areas, in a process also called “feedforward”. Reciprocally, top-down processing involves a “feedback” flow of information, from higher to lower processing areas. Indeed, for visual stimuli, disrupting low-level processing areas impedes their conscious perception (Bullier, 2001).

Grossenbacher and Lovelace (2001) proposed a Disinhibited Feedback Theory of synesthesia, according to which synesthetic experiences arise from a lack of inhibition of feedback information flow. They postulated that, from a so-called “multisensory nexus”, sensory information is sent back to the low-level area it originated from. Normally, this multisensory information is redistributed only to the correct specialized area (e.g., letter information is relayed to the letter processing area), the other types of sensory information being inhibited. In synesthetes, however, a disinhibition occurs, which leads to information being relayed to the “wrong” area (e.g., letter information is sent to the color processing area). The fact that synesthetic experiences can occur as an effect of drugs was interpreted as evidence that the difference between synesthetes and controls is not at the structural level, as connections do not have time to form upon ingesting drugs. Instead, the drugs are causing pathways that are otherwise inhibited to be disinhibited, resulting in the temporary synesthetic experience (Grossenbacher & Lovelace, 2001). This claim though overlooks the phenomenological differences between developmental and pharmacological synesthesia (Bargary & Mitchell, 2008; Hubbard et al., 2011; Hubbard & Ramachandran, 2005; Newell & Mitchell, 2016). Bargary and Mitchell (2008) also argued that the Disinhibited Feedback Theory assumes that there are connections between adjacent brains areas that need to be inhibited, however, it appears that the cortex features “hard” borders where very few crossings happen.

The Re-entrant Theory combines aspects of the Cross-Activation and Disinhibited Feedback theories (Smilek et al., 2001). Unusual feedback from higher-level areas to lower-level areas are hypothesized to occur. In the case of digit-color synesthesia, the multisensory nexus is hypothesized to be located in the anterior fusiform/posterior inferotemporal areas, which are connected to the V4 area of the fusiform gyrus, and possibly to V1 and V2 in the visual area (Smilek et al., 2001). A critical aspect of the Re-entrant Theory is that this feedback process can occur only upon identification of the inducer. As a result, both sensory perception and mental representations of the inducer can cause a concurrent experience.

2.2.4. THE INVOLVEMENT OF CONCEPT ACQUISITION

It has been observed quite early on that semantics play a role in synesthetic experiences. The phenomenon can therefore be a cognitive one, rather than a purely perceptual one.

The very first argument is that some inducers are not perceptual in nature, such as time units or personalities (Day, 2005; Grossenbacher & Lovelace, 2001). Second, most inducers are culturally acquired concepts. Graphemes, time units, and musical scales, to name a few, are only conventions, and can vary from one culture to the other (Day, 2005). Third, synesthetic inducers are often items that convey meaning (Grossenbacher & Lovelace, 2001) and linguistic units are involved as the most prevalent synesthesia inducers, including graphemes, phonemes, words, weekdays, or month names (Day, 2005; Simner et al., 2006).

Grapheme-color synesthesia offers ample opportunity to assess the involvement of semantics. Indeed, color associations seems unaffected by font changes (uppercase, lowercase, block letters, cursive), as well as by voice changes in the case of phoneme-color synesthesia (i.e., male or female voice) (Grossenbacher & Lovelace, 2001). Also, the language modality (i.e., spoken, written or signed) does not change the color of the synesthetic percept (Atkinson et al., 2016). As such, it seems that it is the abstract identity of the grapheme that triggers that color concurrent, as not its perceptual properties. Imagining the inducer is also enough to cause a concurrent experience (Cytowič, 2002a), further demonstrating that sensory information needs not be involved. Ambiguity-solving also sheds light on the conceptual level of synesthesia. When shown a “5” drawn only using “3” symbols (Fig. 2-2), synesthetes perceived the color of the 5 or of the 3, depending on whether they focused on the general 5-shape or the small 3s (Ramachandran & Hubbard, 2001b). In a similar manner, when presented with an ambiguous grapheme (Fig. 2-2) that can be read as either an “A” or an “H”, synesthetes perceived the color of an A if the surrounding letters are “C_T”, but the color of an H if it is surrounded by “T_E” (Ramachandran & Hubbard, 2001b). This “THE/CAT” manipulation demonstrates that it is not the surface features of the graphemes that trigger a color experience, but rather the interpretation of the stimuli.

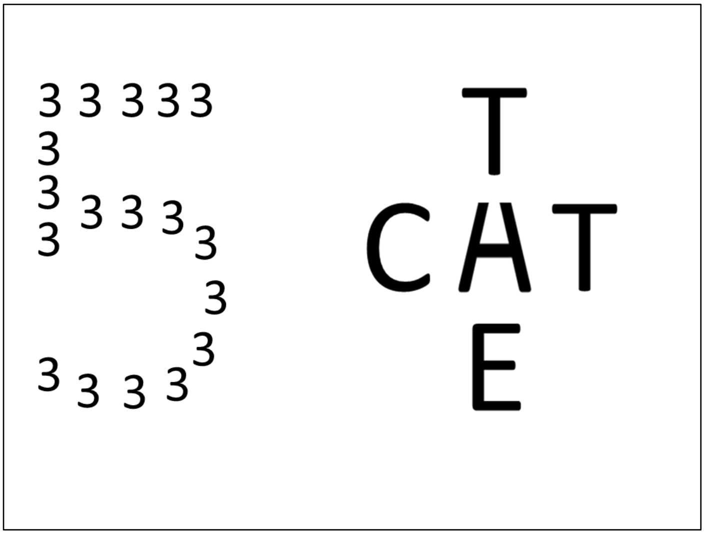

Figure 2-2. Ambiguous stimuli, adapted from Ramachandran & Hubbard (2001b). On the left, a 5 written using 3s. Digit-color synesthetes perceived different colors depending on whether they focused on the whole picture (the 5) or the constituting items (3s). On the right, an ambiguous grapheme that can be interpreted as an A or H, depending on its surrounding context. If reading “CAT” synesthetes perceived the color of an A, but when reading “THE” they perceived the color of an H.

Later, it was shown that grapheme-color synesthetes can perceive colors for new graphemes also. A simple transfer effect occurred, where a pseudo-grapheme took the color of the Latin grapheme it was meant to replace (Mroczko et al., 2009). This transfer occurred spontaneously and in only 20 minutes, thus too fast for new anomalous brain connections to be created between grapheme and color areas. More recently, a study showed that adult synesthetes can acquire new associations, not only based on transfer (Uno et al., 2020). Indeed, when presented with new graphemes that replaced graphemes in their native language, synesthetes simply operated a transfer from the old graphemes’ colors to the new graphemes, as previously found (Mroczko et al., 2009). However, when the old graphemes all had the same synesthetic color, the new graphemes each acquired a different color. This showed that synesthetic color might serve a role in distinguishing different grapheme information, thus serving as a categorization method (Uno et al., 2020).

As presented in section 2.1.2, synesthesia can be divided between intramodal and intermodal types (Marks & Odgaard, 2005) and importantly, Marks and Odgaard (2005) pointed out that grapheme-color synesthesia may be the only type of synesthesia reported so far that involves different dimensions of the same modality. This brings in the question of the extent to which synesthesia involve an unusual association between sensory modalities, or whether the association occurs at another level of the inducer and concurrent identity. According to the conceptual-mediation model of synesthesia (Chiou & Rich, 2014), both the inducer and concurrent are linked at the conceptual level. This idea challenges the very definition of synesthesia as a link between sensory modalities. Indeed, evidence both at the neural and behavioral level seem to indicate that synesthetic colors are not the same as real colors (Edquist et al., 2006; Hupé et al., 2012; Laeng et al., 2004; Ruiz et al., 2017; Ward et al., 2010).

Finally, grapheme-color associations in synesthetes seem to appear gradually during childhood and teenage years, following a consolidation process (Simner & Bain, 2013; Sørensen et al., 2016). In a 4-year longitudinal study, grapheme-color synesthete children went from reporting consistent colors for 34% of graphemes at 6-7 years old to 70% at 10-11 years old (Simner et al., 2009; Simner & Bain, 2013). Furthermore, native speakers of opaque languages, meaning languages where the grapheme-phoneme correspondence is not a one-to-one pairing, seem to show a higher prevalence of grapheme-color synesthesia (Watson et al., 2017). The Developmental Learning Hypothesis of synesthesia (Watson et al., 2010; 2014; 2017) has therefore been formulated, proposing that grapheme-color synesthesia may arise as a neural mechanism for acquiring literacy. In other words, the identity of the concurrent aids in guiding and forming an identity for the inducer. Pinna & Deiana (2018) found that physically coloring full words or syllables lowered the reading time and reading errors in dyslexic children and adults. Coloring letters individually led to performances similar to the monochromatic text conditions, however, the letter-color pairing was not consistent. The results indicate that the experience of physical colors on letter does not disrupt reading, contrary to coloring only half of the words. This raises the question whether a consistent and therefore informative letter-color pairing, as experienced by grapheme-color synesthetes, could improve performance (Mannix & Sørensen, 2021).

2.2.5. INFLUENCES FROM THE ENVIRONMENT

A common misinterpretation of the synesthetes' experience is that they merely remember pairings they frequently saw in childhood (Ramachandran & Hubbard, 2001b), with their associations being only memories, rather than true perceptual experiences. It has, however, been shown that the synesthetic experiences are genuine and can be empirically tested (Dixon et al., 2000; Eagleman et al., 2007). Furthermore, it has been shown that non-synesthete participants who have high-memory skills are not able to produce grapheme-color pairings that match the consistency level of synesthetes' concurrents reporting (Simner et al., 2009). At the same time, some evidence points to the fact that synesthetic associations are influenced by the environment. This process does not negate the genuineness of synesthetes' reports, but it rather informs us of how and when the idiosyncratic pairings may arise.

Childhood toys seem to have an influence on the specific pairings in individuals. Monozygotic twins who have been tested over a 6-year period showed digit-color associations that matched a jigsaw puzzle they had as children, but that they had not seen for seven years prior to testing (Hancock, 2006). The authors also pointed out that the colors reported by the twins for the letters did not match another letter jigsaw puzzle they had. The same year, fridge magnets had been found to have probably influenced the associations of another synesthete (Witthoft & Winawer, 2006). In order to show that those influences were not isolated to one individual, Witthoft and colleagues (2015) tested a large set of grapheme-color synesthetes, and found that for about 6% of them the colors matched the ones of the Fisher-Price fridge magnets, the most common brand sold. Furthermore, up to 15% of the synesthetes who were born during the 10 years after the toy was commercialized showed such an influence, whereas none of those who were born at least five years before the commercialization did.

The native language of the synesthetes also has implications in the specific inducer-concurrent pairings. At the phonemic level, similar phonemes tend to appear in both the inducer word and the concurrent taste (Ward & Simner, 2003) of lexical-gustatory synesthetes. At the orthographic level, there is a clear tendency for the initial letter of a color word to dictate the color that will be perceived (Rich et al., 2005; Simner et al., 2005). For example, in native English speakers Y has been found to elicit an experience of yellow for 45% of the participants (Rich et al., 2005). This causes the letter B to be associated to blue in English speakers (Rich et al., 2005; Simner et al., 2005), but then to white (blanco) in Spanish speakers (Root et al., 2021). At the semantic level, in English speakers again, words that are commonly associated with a given letter (i.e., acrophonics) may influence the color associations (Mankin & Simner, 2017). As such, "D" triggers the word "dog", which triggers the color brown (Mankin & Simner, 2017), which had previously been found as a recurring association in 47% of English-speaking synesthetes (Rich et al., 2005). Those tendencies have been found in other languages and cultures (Root et al., 2021). A similar semantic involvement has also been found in lexical-gustatory synesthesia, were the word "blue" may taste "inky" (Simner & Haywood, 2009; Ward & Simner, 2003). At the structural level, the conventions of the writing system seem to influence the associated colors. In an Abugida system, where a consonant and vowel form a single unit with the consonant being the core component and the vowel takes the form of a modifier (or "diacritical mark"), a case study found that the diacritic vowels did not have their own color (Root et al., 2020). Instead, the diacritics "pulled" the color of the main consonant towards the color its associated vowel has if presented in isolation. Thus, for a blue consonant associated to a red vowel, the whole unit will be purplish-blue. Lastly, graphemes with resembling surface properties have been found to have similar colors, but those surface properties differ between alphabets. Asano and Yokosawa

(2013) found that for a Japanese alphabet (i.e., hiragana) ordinality was the strongest factor, followed by sound and visual properties, whereas for English letters only ordinality and visual properties seem to have an influence (Asano & Yokosawa, 2013; Watson et al., 2012).

Other contextual influences have also been identified. First of all, there seems to be a "first item" effect, that biases associations towards red (Root et al., 2017; Rouw et al., 2014). Therefore, first items of a list, such as "A" or "Monday" tend to be associated to red. This applies naturally also to languages that have different alphabet orders than the Latin one, like Korean where the hangul "ㄱ" (K/G) is significantly associated to red (Root et al., 2017). However, a hangul that looks like "A" (ㅈ) or sounds like "A" (ㅏ), does not show such an association to red, demonstrating the "first item" effect. Also, graphemes with resembling surface properties have been found to have similar colors, such as "b" and "d" (Asano & Yokosawa, 2013; Brang, Rouw, et al., 2011; Watson et al., 2012). This process extends to newly acquired graphemes also at both the visual level (Jürgens & Nikolić, 2012) and phonological level (Uno et al., 2020). Finally, cultural stereotypes also seem to play a role, as women with grapheme-color synesthesia show a tendency for associating the initial letter of their first name to pink (Root et al., 2019).

In summary, evidence points toward synesthesia inducer-concurrent pairings crystalizing at a certain point in childhood or teenage years, rather than being present from birth. The case of Japanese orthography is particularly interesting, as in everyday language color words are written using kanji (a non-phonetic writing system derived from Chinese characters). Nevertheless, Japanese adult synesthetes continue to show a bias towards associating the hiragana sign "み" (mi) to the color green, due to the color name "midori" (緑). Root and colleagues (2021) attributed this to the fact that when Japanese children acquire color words, they do not use kanji yet, and only read and write in hiragana.

Overall, environmental inputs appear to play a role in guiding which concurrent will be associated to a given inducer. However, despite commonly occurring patterns appearing at the individual inducer-concurrent level, synesthesia remains a highly idiosyncratic phenomenon, as a given aspect of environmental inputs can lead to a variety of inducer-concurrent associations (e.g., orthographic influences can prompt English speakers to associated the letter B to either blue or brown; Simner et al., 2005). Nevertheless, environmental inputs do not seem to be the only factor involved in the development of synesthesia in individuals, as all the influences listed above are equally present in the environment of non-synesthetes.

2.3. NEUROANATOMICAL PROPERTIES OF SYNESTHESIA

As per the Cross-Activation Theory (Ramachandran & Hubbard, 2001a), synesthesia was hypothesized to be merely an anomalous hyperconnection between the inducer and concurrent areas. However, advances in neuroimaging allowed for measuring differences in various cortical and subcortical areas between synesthetes and non-synesthetes. As it turns out, much more than just the inducer and concurrent areas seem to be involved. Furthermore, EEG and MEG data also allow to inform us about the time course of the synesthetic experiences.

2.3.1. CONCURRENT AREAS

At the functional level, increased activation was found in the V4 area when presenting words auditorily to word-color synesthetes (left area activation: Nunn et al., 2002; Steven et al., 2006) and when presenting graphemes visually to grapheme-color synesthetes (Hubbard, Arman, et al., 2005; Laeng et al., 2011; Specht & Laeng, 2011; Sperling et al., 2006; van Leeuwen et al., 2010). V4 is often reported as the color center of the brain (Bartels & Zeki, 2000; Zeki & Marini, 1998). However, other areas are also important in color processing, such as V1 (Bartels & Zeki, 2000; Engel et al., 1997; Zeki & Marini, 1998). Aleman and colleagues (2001) found V1 activation in a word-color synesthete who listened to words. Steven and colleagues (2006) also found left V1 activation during auditory word presentation to word-color synesthetes.
Similarly, in sequence-space synesthesia Tang and colleagues (2008) found increased activity in the posterior intraparietal sulcus, which has been linked to spatial processing (Sereno et al., 2001) and spatial processing relative to numbers (Hubbard, Piazza, et al., 2005). In lexical-gustatory synesthetes, the activation patterns differed in the left anterior insula, which is implicated in taste processing (Small, 2010), compared to controls when viewing words (Colizoli et al., 2013; Jones et al., 2011). Similarly, in a vision-touch synesthete, increased bilateral insular activation was observed compared to controls, which is hypothesized to reflect activation of the tactile receptive fields of the anterior insula (Blakemore et al., 2005). All those studies seem to confirm activation of the concurrent area during synesthetic experiences.
However, many have failed to find any V4 and/or V1 activation in color-related synesthesia (Bor et al., 2008; Gray et al., 2006; Neufeld et al., 2012; Paulesu et al., 1995; Rich et al., 2006; Rouw & Scholte, 2007, 2010; Sinke, Neufeld, et al., 2012; Weiss et al., 2001, 2005). Rich and colleagues (2006) found increased activation in the left medial lingual gyrus, an area nearby V4, which has been involved in color-related tasks, such as color naming (Price et al., 1996). However, the evidence is not unanimous as deactivation of the left medial lingual gyrus was found when word-color synesthetes heard words (Paulesu et al., 1995), as well as lower activation in grapheme-color synesthetes than controls in the left occipital fusiform and lingual gyrus when viewing letters (O'Hanlon et al., 2013).

Using a Stroop task and a synesthesia variation of the Stroop task, Specht and Laeng (2011) found increased activity in the V4 area of grapheme-color synesthetes. They also found that the further the displayed color is from the synesthetic color, the greater the V4 activation (Laeng et al., 2011). They hypothesized that this could be due to a recruitment of more vision cells to be able to experience several colors simultaneously. They further concluded that activation from synesthetic colors was probably equal to real color experience. However, Hupé and colleagues (2012) and Ruiz and colleagues (2017) found that the areas that responded to real colors were not activated by synesthetic colors.

At the structural level, increased gray matter volumes were found in the V4 area (Jäncke et al., 2009; Weiss & Fink, 2009) of grapheme-color synesthetes and of a tone-color synesthete (Hänggi et al., 2008). However, this same synesthete, who also has interval-gustatory synesthesia, showed decreased gray matter volumes in the insula (Hänggi et al., 2008), relevant of gustatory processing (Small, 2010). Others have, nevertheless, failed to find gray matter volume increase in the V4 area of grapheme-color synesthetes (Hupé et al., 2012; Melero et al., 2013).

Overall, the results regarding automatic activation of the concurrent-related areas in the brain of synesthetes are mixed. Also, even when V4 activation is found in color-related synesthetes, it is not necessarily the case for every participants tested (Sperling et al., 2006). Similarly, increased gray matter volumes of the concurrent areas are not systematically found.

2.3.2. INDUCER AREAS

The brain areas in charge of processing the synesthesia inducers have been hypothesized to be involved during the synesthetic experience. It is, however, not completely clear at what level of inducer processing the synesthesia experience arises. Most research around this question has been carried out on grapheme-color synesthesia.

Grapheme processing has been proposed to follow a hierarchical decoding (Dehaene et al., 2005), where the low-level perceptual aspects of the stimuli are analyzed bilaterally in the V1 area of the occipital cortex (i.e., analysis of line orientation). As the analysis becomes more precise and more conceptual, the seat of cerebral activation becomes more and more anterior, whereby case-specific letter identification (e.g., “E” and “e” are treated as different letters) are hypothesized to take place in bilateral V4 occipital areas, but the abstract level of the letter identity (e.g., “E” and “e” are treated as different realization of the same letter) occur in the bilateral V8 areas (Dehaene et al., 2005). The processing of graphemes combinations, first from bigrams (i.e., two-letter combinations) to quadrigrams (i.e., four-letter combinations) and finally real words then also follows a posterior to anterior progression of activation along the left Visual Word Form Area (Vinckier et al., 2007), a functional area located in the fusiform gyrus.

As presented in section 2.3.1, some MRI studies on grapheme-color synesthetes have found increased connectivity and activity in the V4 area, located in the posterior area of the fusiform gyrus, and interpreted it as involving concurrent processing. Some studies, however, have also found increased functional connectivity (van Leeuwen et al., 2011) and increased activity (van Leeuwen et al., 2010) in the anterior area of the fusiform gyrus, interpreted as reflecting the processing of the inducers. Nevertheless, the mere existence of a Visual Word Form Area is still subject to debates, as the area is also activated during tasks that do not involve word processing, such as picture naming, color naming or repeating auditorily presented words (Price & Devlin, 2003). Furthermore, the hierarchical model (Dehaene et al., 2005) of grapheme identification has been criticized for relying on pure feedforward mechanisms and not taking into account the feedback processes probably involved, by which orthographic knowledge facilitates grapheme identification (Lally & Rastle, 2022).

Chiou & Rich (2014) proposed that the grapheme-color synesthetic experience arises following the "hub-and-spoke" model of conceptual representation (Patterson et al., 2007), by which a "hub" located in the anterior temporal lobe turns perceptual information coming from various modality-specific areas, called "spokes", into conceptual knowledge. According to the authors, grapheme-color synesthesia may take place in the anterior temporal lobe, where the conceptual-level of the grapheme and color become associated. The authors further argue that past studies may have failed to find activation of this area due to methodological issues, namely distortion on MRI data and failure to include this area as a region of interest.

Identifying the brain areas involved in the processing of the inducer in synesthesia turns out to be a significant challenge. At the same time, studies have found that grapheme-color synesthetes tend to have non-typical face processing ability (Mannix & Sørensen, 2022; Sørensen, 2013), a function located in a region homologous of the Visual Word Form Area in the right hemisphere (Dien, 2009).

2.3.3. PARIETAL AREAS

The Cross-Activation Theory was updated in favor of the Cascaded Cross-Tuning model (Brang et al., 2010; Hubbard et al., 2011) in light of the evidence for parietal activation during synesthetic experiences. The superior parietal lobule has shown increased activity in synesthetes. However, this activation has sometimes been found only in the right hemisphere (Paulesu et al., 1995) or bilaterally (Laeng et al., 2011; Weiss et al., 2005). Regarding the inferior parietal lobule, only Laeng and colleagues (2011) found bilateral activation, while others found left hemisphere activation (Neufeld et al., 2012; Nunn et al., 2002; Rouw & Scholte, 2010; Steven et al., 2006; Weiss et al., 2005). Rouw and colleagues (2011), however, noted that some studies found anterior and superior activation but others posterior and inferior activation of the inferior parietal lobule. Overall, the intraparietal sulcus or angular gyrus have been judged as the most consistent area of parietal activation (Hubbard et al., 2011; Rouw et al., 2011).

Transcranial magnetic stimulation (TMS) studies have also shown that disruption of the parietal areas decreased synesthesia Stroop congruency effects (Esterman et al., 2006; Muggleton et al., 2007). Nevertheless, those TMS studies seem to implicate the right parietal areas, while fMRI data involved the left ones.

At the structural level, increased gray matter volume was found in the left intraparietal sulcus (Rouw & Scholte, 2010; Weiss & Fink, 2009). The intraparietal sulcus has been implicated in various multi-sensory functions including visual feature binding (Donner et al., 2002; Robertson, 2003; Shafritz et al., 2002), perceptual organization during multi-sensory experiences (Cusack, 2005) or cross-modal integration (Calvert, 2001). However, it is also involved in the semantic aspects of digits (Holloway & Ansari, 2010; Sokolowski et al., 2017) in both the visual and auditory modalities (Vogel et al., 2017).

The intraparietal sulcus had also been found involved in sequence-space synesthesia (Tang et al., 2008), but was rather interpreted as a proof of activation of the concurrent experience due to its involvement in spatial processing (Hubbard, Piazza, et al., 2005; Sereno et al., 2001).

Similar to results regarding concurrent areas, the data are not unanimous regarding the parietal lobe. No increased gray matter volumes between grapheme-color synesthetes and controls have also been found (Hupé et al., 2012; Melero et al., 2013). Lower activation was even found in grapheme-color synesthetes compared to controls in the left and right inferior parietal lobules (O'Hanlon et al., 2013).

Hupé and Dojat (2015) further argued that the data so far was not convincing enough regarding the role of the parietal lobe in synesthesia, as most studies are underpowered. Moreover, they claimed that past study designs do not allow to safely conclude whether the witnessed parietal activation is due to concurrent-inducer binding or to attention processes. Attention to the inducer has indeed been found to be an important factor in the synesthetic experience (Mattingley et al., 2001), as lack of attention resources to process the inducer abolishes the synesthetic concurrent experience (Rich & Mattingley, 2010). As such, parietal activation in synesthesia has been hypothesized to reflect attention to the inducer (Chiou & Rich, 2014), rather than being due to a binding process.

2.3.4. INSULAR AREAS

While increased activation and/or increased gray matter volumes in the concurrent and parietal areas of synesthetes have been subject to a variety of interpretations, this is even more the case for the insula. Indeed, since the insula may have a role in synesthesia, a variety of hypotheses have been formulated.

Functional MRI studies have found increased activity in the insula of grapheme-color synesthetes (Nunn et al., 2002; Paulesu et al., 1995; Sperling et al., 2006). Though first hypothesized to reflect the conversion of external stimuli into internal ones (Paulesu et al., 1995), increased activation of the insula of synesthetes was then hypothesized to reflect emotional responses (Rouw et al., 2011). Nevertheless, Rouw and colleagues (2011), proposed that increased insular activation may be found in many different types of synesthesia, as synesthetes often report emotional content related to their experience.

The insula is still a poorly understood area of the brain. A wide range of cognitive functions have been found to be supported by the insula and are still source of debates, including visceral responses, somatic pain sensations, auditory processing, gustatory processing, vestibular processing, emotional experience, empathy, risk taking, attention and salience processing, and speech (Uddin et al., 2017). Functional parcellations of the insula have also resulted in a variety of subdivisions, as low as two and up to 13 (Uddin et al., 2017). However, three main distinct functional areas have been proposed: a posterior area (serving sensorimotor, language-related and auditory processing), a dorsal anterior area (serving higher cognitive processing and executive control) and a ventral anterior area (serving emotional and chemosensation processing), each with distinctive functional connectivity networks (Chang et al., 2013; Deen et al., 2011).

Some functional MRI studies that found increased activity in synesthetes reported general right insular activity (Nunn et al., 2002; Paulesu et al., 1995; Sperling et al., 2006) making Rouw and colleagues (2011)'s proposal for insular activation in synesthetes reflecting emotional responses maybe too ambitious given the lack of precise localization.

Increased right anterior insular activation was found in a blind time-space and time-color synesthete (Niccolai, van Leeuwen, et al., 2012). Here, though, this activation was hypothesized to reflect the audio-visual integration process, as the task consisted in hearing words denoting time units (e.g., Monday, night, Easter, seconds) or encoding of spatial information. The right insula had previously been found to be involved in congruent auditory-visual integration (Naghavi et al., 2007). However, the area also encompassed the claustrum, a structure notoriously difficult to distinguish from the insula due to its size and location, and which has been showed to lead to erroneous interpretation of anterior insula activity in non-human primates (Reser et al., 2017). Multi-sensory integration could therefore involve the claustrum more than the anterior insula (Smythies et al., 2012).

Increased left anterior insular activation was found in lexical-gustatory synesthetes (Colizoli et al., 2013) when presented with tasteful compared to tasteless words. The results were interpreted by the authors as reflecting the concurrent taste experience. However, the results do not show a ventral rather than dorsal anterior insular activity, not allowing to fully conclude for chemosensation processing or emotional processing rather than higher cognitive processing, based on previously defined functional areas of the insula (Chang et al., 2013; Deen et al., 2011). However, in lexical-gustatory synesthetes, left anterior ventral insular activity was found in lexical-gustatory synesthetes when presented with words that produced unpleasant tastes (Colizoli et al., 2013; Jones et al., 2011), in line with the involvement in chemosensation processing and emotional processing of the ventral anterior insula (Chang et al., 2013; Deen et al., 2011). Nevertheless, the left lateralization of the unpleasant taste experiences is contrary to previous studies having found left anterior insular activity for positive emotional stimuli and bilateral anterior insular activity for negative emotional stimuli (Duerden et al., 2013) in the tactile, gustatory, auditory and olfactory modalities.

In mirror-touch synesthesia, increased bilateral insular activation (Blakemore et al., 2005) has been hypothesized to reflect self-awareness and awareness of others (Banissy et al., 2011), as well as processes to differentiate the self from others (Banissy & Ward, 2013; Ward & Banissy, 2015). However, the increased insular activation could not be replicated once increasing the number of mirror-touch synesthete participants (Holle et al., 2013).

At the structural level, increased gray matter thickness was found in the insula of grapheme-color synesthetes (Jäncke et al., 2009). Decreased gray matter volume was found, however, in the left insula of an interval-taste and tone-color synesthete (Hänggi et al., 2008).

The involvement of the insular areas in synesthesia is still not very clear. If the insular areas are truly part of the synesthetic processes, this would indicate that the synesthetes' brains do not differ simply at the level of the concurrent areas and inducer-concurrent binding areas. As such, a larger brain network may be involved in synesthesia.

2.3.5. FRONTAL AREAS

The frontal brain areas have been proposed as part of a fronto-parietal network which provides cognitive control during the synesthetic experience (Chiou & Rich, 2014). Indeed, synesthetes must process and distinguish between both the inducer and concurrent information at the same time.

This double processing is hypothesized to be the reason for increased activity found in the right dorsolateral prefrontal cortex of synesthetes (Aleman et al., 2001; Bor et al., 2008; Laeng et al., 2011; Paulesu et al., 1995; Sperling et al., 2006). Cognitive control has indeed been found to involve the left (MacDonald et al., 2000) and right (Kerns et al., 2004) dorsolateral prefrontal cortex during the Stroop task. More precisely, increased activity in the dorsolateral prefrontal cortex during a task-switching paradigm (i.e., name the displayed color or read the displayed color word) was correlated to smaller Stroop interference. Behaviorally, grapheme-color synesthetes showed slower response times in a similar task-switching Stroop paradigm compared to a standard Stroop one. However, their response times did not significantly differ from controls, showing that the task-switching paradigm did not require more cognitive control in synesthetes than controls (Rouw et al., 2013), possibly reflecting a similar activity of the dorsolateral prefrontal cortex in both groups (Kerns et al., 2004; MacDonald et al., 2000). In line with the negative correlation between response times and dorsolateral prefrontal activation previously described (Kerns et al., 2004; MacDonald et al., 2000), Laeng and colleagues (2011) found that slower response times were associated with larger prefrontal activation, and faster response times were associated with smaller prefrontal activation during a standard Stroop and a synesthesia Stroop paradigm in both synesthetes and controls.

More specifically, naming the displayed color while ignoring the synesthetically experienced one caused smaller congruency effects and higher prefrontal activation, while naming the synesthetically experienced color caused higher congruency effects and smaller prefrontal activation.

MacDonald and colleagues (2000) and Kerns and colleagues (2004) also found a dissociation regarding cognitive control between the dorsolateral prefrontal cortex and the anterior cingulate cortex, which is adjacent to the medial frontal cortex. Indeed, the dorsolateral prefrontal cortex appears involved in implementing control, while the anterior cingulate cortex is involved in conflict monitoring and error adjustment. The anterior cingulate cortex was therefore more activated during incongruent than congruent trials, but was not involved in task-switching (MacDonald et al., 2000). Despite being active for different aspects of cognitive control, both brain regions seem to still work in collaboration, as increased anterior cingulate cortex activity during an incorrect trial led to increased prefrontal activity in the following trial (Kerns et al., 2004). In line with those findings, the dorsolateral prefrontal cortex did not show increased activity when having to process incongruent stimuli in a standard and a synesthesia Stroop task in synesthetes (van der Veen et al., 2014). Instead, the anterior part of the cingulate cortex, showed increased activity when synesthetes named the displayed color during neutral trials of the standard Stoop and during the incongruent trials of the synesthesia Stroop (van der Veen et al., 2014). At the same time behaviorally, synesthete participants showed a reduced interference in the standard Stoop, due to interference also occurring in the neutral condition, and increased interference in the synesthesia Stroop, compared to controls (van der Veen et al., 2014).

On and on, those results indicate that increased activity both in the dorsolateral prefrontal cortex, for complex tasks that require more cognitive control in order to successfully ignore the irrelevant information, and in the anterior cingulate cortex, in order to monitor the accuracy of the provided response, can reflect the double processing of conflicting physical and synesthetic colors.

Other interpretations of lateral prefrontal activation have been proposed. Bor and colleagues (2008) interpreted increased bilateral lateral prefrontal activation in a grapheme-color synesthete compared to controls during a digit span task as relevant of chunking processes and non-mathematical structuration of digit information. The study was, however, run on a synesthete with extraordinary memory ability, questioning the degree to which the results can be generalized to the whole synesthete population.

Increased activations in the frontal cortex of grapheme-color synesthetes seem, however, more diffuse than the other areas previously described. A variety of areas have shown significant activation, including the inferior frontal gyrus (left: Aleman et al. (2001); Laeng et al. (2011); Sperling et al. (2006); right: Aleman et al. (2001); Laeng et al. (2011)), the left central and frontal opercular cortex (Laeng et al., 2011), the middle frontal gyrus (left: (Rouw & Scholte, 2010); right: Aleman et al. (2001); Laeng et al. (2011)), the right paracingulate gyrus (Nunn et al., 2002), the precentral gyrus (left: Laeng et al. (2011); Nunn et al. (2002); Rouw & Scholte (2010); Weiss et al. (2005); right: Laeng et al. (2011); Paulesu et al. (1995)), the left premotor cortex (Laeng et al., 2011) and the right superior frontal gyrus (Nunn et al., 2002; van Leeuwen et al., 2010).

Sperling et al. (2006) interpreted the frontal activation as part of a network of color processing, more specifically, dedicated to object color identification. Nunn and colleagues (2002) on the other hand, interpreted increased activity in the right paracingulate gyrus as relevant of episodic memories attached to the synesthetic experience.

The frontal cortex is involved in a wide range of processes, including problem-solving, judgment, decision making, abstract thinking, inhibitory control, reasoning, maintaining social behavior, personality expression. A large variety of tasks was used in functional MRI studies finding frontal activity in synesthetes, such as a passive listening task (Aleman et al., 2001), a verbal fluency task (Aleman et al., 2001), a Stroop task (Laeng et al., 2011; van der Veen et al., 2014), a synesthesia Stroop task (Laeng et al., 2011; van der Veen et al., 2014), a grapheme viewing task (Rouw & Scholte, 2010; van Leeuwen et al., 2010; Weiss et al., 2005), a word listening task (Nunn et al., 2002), a color viewing task (Nunn et al., 2002), a priming task (van Leeuwen et al., 2010). Involvement of the frontal cortex in synesthesia may therefore be task-dependent, as cognitive control could be expected to be more central during a Stroop task than a passive listening task.

Increased frontal activation in synesthetes could reveal engagement of higher-level processes. However, the neural hypotheses of synesthesia previously presented tend to confine higher-level processes of inducer-concurrent binding in the parietal lobe. Lastly, few studies that found increased activation in the frontal areas ventured an interpretation that favor any of those hypotheses.

2.3.6. BRAIN CONNECTIVITY

Finding increased activity or greater gray matter volumes in the concurrent, parietal, insular or frontal areas only tells part of the story. Hypotheses regarding the origins of synesthesia also implicate better communication between those areas. Therefore, it is important to also evaluate whether those various brain areas are more densely connected.

Some studies found connectivity between brain areas that support the Cross-Activation Theory, according to which synesthesia results from hyperconnectivity between the inducer and concurrent areas (Ramachandran & Hubbard, 2001a). Fractional Anisotropy was measured between grapheme-color synesthetes and controls (Rouw & Scholte, 2007). Fractional Anisotropy measures the degree to which water molecules travel freely in any direction in the brain. Low Fractional Anisotropy indicates that the movements of water molecules are unrestricted and can therefore move in any direction. A high Fractional Anisotropy on the other hand indicates restriction of movement in a single direction, indicating the presence of a fiber track. Grapheme-color synesthetes had higher Fractional Anisotropy in the right inferior temporal cortex and in the left superior parietal cortex than controls. This right inferior temporal area appeared to be nearby the fusiform gyrus, and close to the inferior longitudinal fasciculus which connects the occipital and temporal lobes. Higher Fractional Anisotropy was also found in the bilateral superior frontal areas, as part of a track projecting to the corpus callosum. This high Fractional Anisotropy was hypothesized by the authors as due to superior connectivity, rather than difference in the orientation of fiber tracks. Nevertheless, the results are not a clear demonstration of hyperconnectivity between the inducer and concurrent areas, as no structural differences were found in the Visual Word Form Area of the fusiform gyrus nor in the color processing areas V1/V4 precisely.

Similarly, when using the same method, although increased Fractional Anisotropy was found in areas that seem to match perfectly with the inducers and concurrents of an interval-taste and tone-color synesthete (i.e., Heschl's gyrus: auditory processing; insula: taste processing; lateral superior occipital cortex: visual processing), no significant increased Fractional Anisotropy was found near the color processing areas of the occipital cortex (Hänggi et al., 2008). Furthermore, Jäncke and colleagues (2009) failed to find the significant increased Fractional Anisotropy in the fusiform gyrus of grapheme-color synesthetes previously claimed by Rouw & Scholte (2007).

Hänggi and colleagues (2008) and Rouw & Scholte (2007), both suggested that their results support the Cross-Activation Theory, showing an hyperconnectivity between inducer and concurrent areas. However, as highlighted by Hänggi and colleagues (2008), an hyperconnectivity could equally be the consequence, rather than the cause, of the synesthetic experiences. Following a Hebbian Learning (1949) postulate, experience-dependent plasticity (Chugani, 1994; Hua & Smith, 2004) could account for the increased connectivity between inducer and concurrent areas, as the synesthete tested by Hänggi and colleagues (2008) uses their synesthetic concurrent experience in order to identify intervals and tones. Numerous studies have indeed found that synesthetes have a particular relationship to their synesthetic experiences, with sequence-space synesthetes reporting using their experiences to carry calculations (Mealor et al., 2016), grapheme-color synesthetes having potentially transferred their colors for graphemes to note names (Ward, Tsakanikos, et al., 2006) or reporting using their synesthesia in their everyday life (Rothen, Tsakanikos, et al., 2013).

Some studies, have found connectivity between brain areas that support the Cascaded Cross-Tuning model, by which synesthesia is a two-step phenomenon, starting with hyperconnectivity between inducer and concurrent areas and finishing with binding in the parietal cortex (Hubbard et al., 2011).

Weiss & Fink (2009) found that gray matter volume was positively correlated between the fusiform gyrus and the caudal intraparietal sulcus in grapheme-color synesthetes, supporting the Cascaded Cross-Tuning model. Nevertheless, when looking at brain areas in isolation, gray matter volumes increase was found in the right fusiform gyrus and in the left intraparietal sulcus.

A small-world analysis was conducted on resting state EEG of synesthetes who experience colors when hearing grapheme names (Jäncke & Langer, 2011) to test the presence of a parietal hub, as per the Cascaded Cross-Tuning model. This type of analysis evaluates how a given node's neighbors are likely to be neighbors of each other. A stronger hub, interpreted as revealing hyperconnectivity, was found in the parietal and auditory cortices of synesthetes, confirming the Cascaded Cross-Tuning model according to the authors. Nevertheless, no hub was found in the fusiform gyrus. It was also pointed out that the low number of participants and high number of region comparisons makes it impossible for the significant results to survive multiple comparisons (Hupé & Dojat, 2015), rendering the support to the Cascaded Cross-Tuning model quite weak.

In a functional connectivity analysis, increased functional connectivity was found between the right frontoparietal and the lateral visual and auditory areas of grapheme-color synesthetes (Dovern et al., 2012), supporting the Cascaded Cross-Tuning model. However, upon reanalysis of the data, it appears that only frontoparietal networks survive multiple comparison, which has never been hypothesized as implicated in any synesthesia model (Hupé & Dojat, 2015).

Some studies found support for the Disinhibited Feedback Theory, which hypothesizes a lack of inhibition of the feedback information flow from the parietal to the low-level processing areas (Grossenbacher & Lovelace, 2001).

A functional connectivity analysis was carried on music-color synesthetes (Neufeld et al., 2012a). Although no difference was found regarding the connectivity of the auditory, visual, and parietal areas in isolation, an increased connectivity between the left inferior parietal lobule and the left primary auditory and right primary visual cortex appeared in synesthetes compared to controls. The authors interpreted the results as supporting the Disinhibited Feedback Theory. The lack of increased connectivity between the auditory and color areas was further interpreted as not supporting the Cross-Activation Theory. Nevertheless, the left lateralization found in the primary auditory cortex is contradictory to the asymmetrical functional organization of sound processing, with speech sound processing occurring on the left side and music sound processing on the right side (Tervaniemi & Hugdahl, 2003). The increased connectivity between the left inferior parietal lobule and the left primary auditory may therefore not be reflective of a link between the parietal lobe and the low-level area responsible for inducer processing. In a previous analysis of the same data, a bilateral primary auditory cortex activity was found (Neufeld et al., 2012b), casting doubt on the reliability of the findings. The Disinhibited Feedback Theory also does not serve as an explanation for why only the right primary visual cortex would be involved in feedback process from the left parietal area. Similarly, in grapheme-color synesthetes, functional connectivity analysis found greater functional connectivity between the right inferior parietal lobule and the right primary and secondary visual areas (Sinke, Neufeld, et al., 2012), prompting the authors to call for an updated version of the Disinhibited Feedback Theory, where feedback may not occur directly to the V4 areas, but rather to V1/V2, which is then forwarded to V4. However, here again, no account regarding the lateralization of activity of the primary and secondary visual areas is provided. Lateralization is not addressed neither in a resting state EEG study by Brauchli and colleagues (2018) that found increased connectivity between the superior parietal lobule and the left V4 area in sound-color synesthetes. These results were nevertheless interpreted as supporting the Disinhibited Feedback Theory due to the top-down nature of the information flow (Brauchli et al., 2018). Similarly, in music-color synesthetes again, Zamm and colleagues (2013) found increased Fractional Anisotropy only in the right inferior fronto-occipital fasciculus, which connects frontal brain areas to auditory and visual association areas. The authors, however, did not venture an interpretation in favor of either the Cross-Activation Theory or Disinhibited Feedback Theory, as increased Fractional Anisotropy may be equally due to lack of inhibitory crossing fibers or reflect hyperconnectivity.

Finally, some studies found support for global differences between the synesthetic and non-synesthetic brain.

Connectivity was measured in grapheme-color synesthetes and controls using a small-world analysis (Hänggi et al., 2011) on fMRI data. The results indicated greater local hyperconnectivity, possibly involving greater network efficiency and higher information processing and integration in synesthetes. However, this hyperconnectivity was not restricted to the fusiform gyrus. The small-world architecture also differed greatly between synesthetes and controls, the former showing a somewhat unbalanced organization, with increased global hyperconnectivity. The authors argued that synesthesia may be only one of the several consequences of such an unusual organization. Although local efficiency may be increased in synesthetes, global efficiency could be decreased, and a lower modularity may have effects at the function level, such as increased memory or creativity (Hänggi et al., 2011). Moreover, a version of the small-world analysis focusing only on the fusiform gyrus found lower connectivity in synesthetes (Hänggi et al., 2011). Hupé & Dojat (2015) asserted that such results were clearly in conflict with the Cross-Activation Theory.

However, the global differences between synesthetes and control are not fully established, as no difference in global hyperconnectivity was found in the resting EEG paradigm using the same analysis (Jäncke & Langer, 2011).

Overall, results concerning brain connectivity in synesthetes are quite mixed. This type of analysis suffers even more from the low number of participants as multiple comparisons need to be performed, and many failed to reach significance after proper correction. To date, no study has been able to rule unanimously in favor of any model of synesthesia unfortunately.

2.3.7. TIME COURSE OF ACTIVATIONS

FMRI data analyses suffer from low temporal precision. Nevertheless, information regarding the time course of neural activations in synesthesia is an important aspect in understanding its underlying mechanism (Hubbard, 2007).

In an EEG study, grapheme-color synesthetes and controls were presented with visual stimuli that activate either the parvocellular or magnocellular system of the thalamus (Barnett, Foxe, et al., 2008). Critically, none of those stimuli were synesthetic inducers. Results showed a tendency towards decreased magnocellular activation and significantly increased parvocellular activation, around 65-85ms after stimuli onset, in synesthetes. The parvocellular cells provide visual information coming from the cones of the retina to the temporal/ventral stream, or “what” pathway, through V1 and are mostly concerned with color information. The magnocellular cells on the other hand convey visual information coming from the rods of the retina to the parietal/dorsal stream, or “where” pathway, through V1 and are mostly devoted to brightness and motion information. Differences in those early visual processes are hypothesized to potentially be due to a greater development of the color pathway in some individuals, which causes abnormal color co-activation when new information, such as graphemes, is acquired (Barnett, Foxe, et al., 2008). A more developed color pathway, however, does not explain the variety of inducer-color pairs, and why some synesthetes would experience colors for a certain type of new information (e.g., graphemes), while other synesthetes would experience colors for a whole different type of information (e.g., music).

Early sensory processes were investigated in sound-color synesthetes, who showed smaller auditory-evoked potentials N1 (100-140ms), P2 (205-245ms), and N2 (290-330ms) than controls, when presented with color-inducing sounds (Goller et al., 2009). N1 and N2 activity differences were located at the frontal site and P2 around the central site. When presented with non-synesthesia-inducing colors, those synesthetes showed reduced visual-evoked potential N1 (120-160ms) compared to controls. The results did not validate the Cross-Activity Theory, as no multisensory ERP differences were found between synesthetes and controls, however, the reduced auditory-evoked and visual-evoked potentials could indicate core differences in sensory processing in synesthetes. Nevertheless in another study, synesthetes who perceive colors when hearing sounds and words showed a larger negative activity than controls in the left V4 and orbitofrontal areas 122ms after stimuli onset (Beeli et al., 2008). This early activity in the color area was interpreted as reflecting the automatic and possibly bottom-up nature of the synesthetic color experience, thus supporting the Cross-Activity Theory. The source reconstruction method used (low-resolution brain electromagnetic tomography), although having showed good localizations (Yao & Dewald, 2005), suffers from a low spatial resolution of about 6mm (Yao & Dewald, 2005). The volume of hOC4v, the anatomical substrates seemingly corresponding to the function V4 area, shows great size variations between individuals (Rottschy et al.,

2007). Furthermore, when normalized to the MNI single-subject reference space, as performed by (Beeli et al., 2008), the probability to correctly discriminate the hOC3v (V3), hOC4v (V4), BA 17 (V1), and BA 18 (V2) structures was low (Rottschy et al., 2007). Finally, regarding V4 as the color area may be an over-simplification, as the exact seat of color processing is not yet settled and has been argued to occur rather in the V8 area (Hadjikhani et al., 1998), an area anterior to ventral part of V4, casting doubt on whether early color activity truly occurs in sound-color synesthetes.
A similar greater N1 (80-180ms) activity, found in the occipital site in sound and/or grapheme-color synesthetes compared to controls, has been interpreted as a global difference in sensory processing in synesthetes (Sinke et al., 2014). This conclusion stemmed from the fact that greater N1 was present in synesthetes regardless of the modality (visual or auditory) or congruency of the stimuli.

The effect of congruency was investigated in an EEG study in grapheme-color synesthetes (Brang et al., 2008), tapping into more top-down processes. The congruent condition showed a larger N1 (100-150ms) activity at the occipitotemporal site, a smaller P2 (150-250ms) activity at the frontal site and smaller N400 (300-450ms) activity across the scalp. The authors though did not interpret the result in favor of any model of synesthesia. However, when comparing activity between synesthetes and controls trained on grapheme-color associations, the N1 and N400 activity in the congruent condition was similar to those elicited by mere colored graphemes viewing (Brang, Kanai, et al., 2011). The decreased frontal P2 (150-250ms) was the only component proper to synesthetic experiences, possibly reflecting conscious experiences (Brang, Kanai, et al., 2011). Another study using trained non-synesthetes found differences between them and genuine synesthetes only regarding a larger and earlier N170 (100-200ms) activity in the incongruent condition for synesthetes (Niccolai, Wascher, et al., 2012). Congruency showed similar late processes, such as reduced N300 (200-320ms) and N400 (320-420ms), in both trained non-synesthetes and synesthetes. The results thus reflected early sensory processing, which distinguish between genuine synesthesia and learned associations (Niccolai, Wascher, et al., 2012).

A core aspect of the Cross-Activation Theory and Cascaded Cross-Tuning model is the simultaneous activity in the inducer and concurrent areas. Nevertheless, some of the previously presented studies only found different activation of those areas in isolation (Beeli et al., 2008; Brang et al., 2008; Sinke et al., 2014). When presenting grapheme-color synesthetes and controls with graphemes, MEG data found an almost simultaneous activity in the posterior temporal grapheme area (105-109ms) and V4 (110-114ms) area in synesthetes (Brang et al., 2010). The authors argued their results supported the Cascaded Cross-Tuning model. However, analysis was conducted only on those two areas, ignoring possible activation in other areas. Furthermore, only four synesthetes were tested, which has been criticized for statistical power reasons (Hupé & Dojat, 2015). Finally, a L1-minimum-norm method was used in order to reconstruct the localization of the source of activity. This method was found to perform worse than the low-resolution brain electromagnetic tomography method previously used by Beeli and colleagues (2008), regarding error in distance to actual activity location, undetected sources and falsely detected sources (Yao & Dewald, 2005), especially in the outermost cortex (Asadzadeh et al., 2019). This is a severe issue, given the close proximity of the two investigated areas, adding up to the previously presented debate on V4 regarding its localization and role in color processing (Hadjikhani et al., 1998; Rottschy et al., 2007).

Regarding later processes, no differences were found concerning the later components (200-420ms) of sound and/or grapheme-color synesthetes compared to controls (Niccolai, Wascher, et al., 2012; Sinke et al., 2014). However, when presented with color-inducing sounds, controls showed a slow negative activity at 400-800ms at the centrofrontal site, which was completely absent in synesthetes (Goller et al., 2009). On the other hand, an earlier ERP study found increased positive activity at the frontal and central sites of grapheme-colors synesthetes compared to controls starting from 150ms after stimuli presentation, and most prevalent between 300 and 600ms (Schiltz et al., 1999). No differences were found around the parietal electrodes regarding those late processes. These results were interpreted as either a possible lack of inhibition over those frontal areas in synesthetes or greater multisensory processing.

The Cross-Activation Theory posits that synesthetic color experiences are due to activity in the early visual areas. Teichmann and colleagues (2021) used a classification model trained on MEG data collected during viewing red and green stimuli to investigate whether viewing black graphemes that cause red and green synesthetic color experiences results in activity that correspond to middle-level (60-80ms) color perception, as per the Cross-Activation Theory. The neural signal could be decoded as belonging to viewing a red or a green stimuli between 80ms and 200ms, in line with more recent research on color decoding from EEG data (Chauhan et al., 2021). Critically, neural activity found at 200ms for colored stimuli viewing corresponded to neural activity at 300ms to 400ms during black grapheme viewing, indicating that synesthetic color experience corresponds to late real color processing (around 200ms), rather than early color processing (before 200ms). The results, nevertheless, did not show whether earlier activity patterns during real color viewing (around 80ms) also corresponded to any time point during synesthetic color experiences.

Overall, synesthetes show differences in early processes, regardless of whether the presented stimuli induce a synesthetic experience of not. Some interpreted those results as evidence of global sensory processing differences in synesthetes (Goller et al., 2009; Niccolai, Wascher, et al., 2012; Sinke et al., 2014). Others, argued that the time course of activity reflects the bottom-up aspect of synesthesia, supporting the Cross-Activation Theory or Cascaded Cross-Tuning model (Beeli et al., 2008; Brang et al., 2010). However, top-down processes seem also implicated in the data, both early (150-250ms) at the frontal site (Brang, Kanai, et al., 2011) and later (300-800ms) at the frontal and central sites (Goller et al., 2009; Schiltz et al., 1999), possibly reflecting the lack of inhibition in synesthetes (Schiltz et al., 1999), as per the Disinhibited Feedback Theory or a synesthetic experience occurring at the conceptual-level (Teichmann et al., 2021).

2.3.8. PHENOMENOLOGICAL DIFFERENCES

Developmental synesthetes differ from each other at several levels. First, at the most specific level, the idiosyncratic aspect of synesthesia causes the pairings to greatly differ (the number 2 can be red, but it can also be green depending on the individual). Second, the range of synesthetic experiences can greatly vary, where some only experience digit-color synesthesia but others would experience over five different types of synesthesia. Finally, the location of the experience, regardless of the type of synesthesia can be either internal or external, with associator and projector synesthete categories (Dixon et al., 2004). While no neural imaging study has so far been able to show differences between a synesthete who experience the number 2 as red compared to another one would experience it as green, some of the studies previously detailed showed different neuroanatomical and functional activity patterns depending on the particular variety of inducer-concurrent pairings. Moreover, the associator/projector dichotomy has also received attention in neuroimaging studies.

Fractional Anisotropy was increased in the inferior temporal cortex, nearby the fusiform gyrus, of projector compared to associator grapheme-color synesthetes (Rouw & Scholte, 2007). Superior parietal and frontal cortices areas, however, showed no Fractional Anisotropy differences between subtype of synesthetes.

Gray matter volume increase was found in projector compared to associator grapheme-color synesthetes in the V1 (anterior intracalcarine sulcus), auditory (right Heschl’s gyrus, right insula, right parietal operculum) and motor (left precentral gyrus) areas (Rouw & Scholte, 2010). These regions take on primary/secondary sensory and action planning functions. Associators, on the other hand, showed increased gray matter volumes in the hippocampal area (hippocampus, right thalamus, right amygdala, left parahippocampal gyrus, left temporal fusiform gyrus), right cerebellum and bilateral angular gyrus (left superior temporal lobe, right intraparietal sulcus, right superior parietal lobe). These regions are mostly related to memory, including spatial memory, and to phoneme-grapheme conversions during reading and writing (Geschwind, 1972), relating to the hypothesis that grapheme-color synesthesia may support reading acquisition (Mannix & Sørensen, 2021; Watson et al., 2010, 2014, 2017). The superior posterior parietal cortex showed, however, no difference between subtypes of synesthetes. Overall, projectors present differences in the brain areas that are involved in the perception of the outside world, whereas associators do so in areas that involve internal processes (Rouw & Scholte, 2010), reflecting their phenomenological differences.

Van Leeuwen and colleagues (2011) used dynamic causal modeling on fMRI data in order to infer the patterns and directions of interactions of brain areas in associator

and projector grapheme-color synesthetes. They tested a bottom-up model, by which the letter-shape area of the fusiform gyrus activates the V4 color area of the fusiform gyrus to then activates the superior parietal lobe, following the assumptions of the Cascaded Cross-Tuning model (Hubbard et al., 2011). They also tested a top-down model, where the letter-shape area of the fusiform gyrus activates the superior parietal lobe, which then activates the V4 color area of the fusiform gyrus, as per the Disinhibited Feedback Theory (Grossenbacher & Lovelace, 2001). They found that the bottom-up model fitted better projectors' data, while the top-down model fitted associators' data. Projectors' external experiences are therefore explained by bottom-up processes, while associators' internal experiences reflect top-down processes.
In an EEG study, increased alpha-band oscillations were found around the posterior parietal electrodes of projector grapheme-color synesthetes (Cohen et al., 2015). The involvement of alpha-band oscillations in inhibition of sensory processes is hypothesized by the authors to demonstrate a suppression of top-down processes in the parietal areas, which facilitates stronger bottom-up processing instead in projectors.

Finally, the Coloured Letters and Numbers (CLaN) questionnaire (Rothen, Tsakanikos, et al., 2013) has been used to differentiate grapheme-color synesthetes based on the automaticity/attention and localization of the concurrent. High automaticity/attention scores mean that concurrent experiences are more automatic and that less attention to the inducer is needed. Higher localization scores mean that the concurrent is experienced at a specific point in space. This classification differs from the projector/associator one, as high localization can be in the internal or external space.
Grapheme-color synesthetes with high localization scores showed greater bilateral V4 activity, while higher automaticity/attention scores showed only greater left V4 activity (van Praag et al., 2016). Furthermore, synesthetes with higher localization scores showed higher activity in the left precentral gyrus, left supplementary motor area, left anterior intraparietal sulcus, left insula and right cerebellum. The localization items of the CLaN questionnaire include capacity to point at and move the location of the concurrent in space. This is hypothesized as the reason for higher activation of the motor areas (van Praag et al., 2016) for high localization scores. The authors, however, did not provide accounts for the higher insular, cerebellar, and intraparietal activations in high localization individuals.

More research is needed to evaluate neural implications of different phenomenological synesthetic experiences. Not having differentiated between phenomenological experiences has been hypothesized to be the underlying reason for such conflicting results in the history of synesthesia neuroimaging (van Leeuwen et al., 2011; van Praag et al., 2016). However, as presented in Section 2.1.2, synesthesia can be classified in a variety of manners (projector vs associator, higher vs lower synesthetes, conceptual vs perceptual synesthesia, intramodal vs intermodal synesthesia).

Moreover, subgroup comparisons imply recruiting more participants, which is a highly difficult task in synesthesia research. Indeed, low statistical power in neuroimaging studies of synesthesia have been criticized (Hupé & Dojat, 2015). Furthermore, failure to replicate findings concerning differences between grapheme-color synesthetes and controls regarding gray matter volume, sulci morphology, and connectivity (Dojat et al., 2018) raises the question of reproducibility of results altogether.

CHAPTER 3. MEASURING COLOR ASSOCIATIONS IN SYNESTHETES AND THE GENERAL POPULATION

A key aspect of synesthesia and cross-modal correspondence research resides in reliably identifying and quantifying those multisensory experiences. The differing properties of these two phenomena mean that their assessment comes with different opportunities and limitations. Synesthesia is an idiosyncratic, conscious, and consistent phenomenon (Simner, 2012; Ward, 2013). This implies that detection of synesthesia can happen at the individual level and can rely on the synesthetes' ability to clearly report their experiences. Cross-modal correspondence on the other hand is greatly shared across the whole population and is unconscious. It can therefore better be found at the group level and may prove difficult for individuals to precisely describe the associations.

In the field of synesthesia, much work has been focused on trying to establish the nature of the phenomenon (e.g., its consistency, its automaticity, its perceptual aspect) and to understand its origin. Most studies have focused on grapheme-color synesthesia. This bias exists mainly for practical reasons. First, although the claim is not completely settled, grapheme-color synesthesia appears to be the most common type reported (Day, 2022; Ward & Simner, 2022), and thus offers a larger pool of participants. Second, graphemes are stimuli that are easy to deliver to the participants, either visually or auditorily and form an exhaustive list (e.g., 26 letters in English, 29 letters in Danish, 10 digits). Finally, colors are easy to report to a quite precise degree and are easily quantifiable. Overall, the properties of graphemes and colors make quantitative analyses of the synesthetic experience simpler to handle. As a comparison, emotion-smell synesthesia would be harder to sample precisely, due to difficulty in evoking a certain emotion on demand, and issues with accurately reporting smells for subsequent quantitative analyses, paired with a lower prevalence in the population.

Regarding cross-modal correspondence, the choice of pairings to study is not guided by availability of participants, as the phenomenon occurs in the general population. A large body of research is centered around trying to establish which precise associations exist (e.g., high pitches are associated to high lightness, or the color red associated with sweet tastes). Cross-modal correspondence research is most prolific when it comes to auditory-visual correspondences (see Spence (2011) for a review) and this mainly for historical reasons. Sound symbolism, by which speech sounds are thought to contain meaning, as illustrated by the famous kiki/bouba effect (Köhler, 1929; Ramachandran & Hubbard, 2001b), was the first type of cross-modal association studied (Jespersen, 1922; Köhler, 1929; Newman, 1933; Sapir, 1929). Around the same period, the loudness property of non-speech sounds, had also been found to map into the visual modality, with louder sounds being perceived as brighter (Cohen, 1934; Hornbostel, 1938). Later, many aspects of sound have continued to be studied in the light of their visual associations, such as loudness (Marks, 1974, 1987) or pitch height (Evans & Treisman, 2010; Hamilton-Fletcher et al., 2017; Marks, 1974, 1987) as well as the musical aspects of sounds, such as tempo (Palmer et al., 2013, 2016) or musical mode (Palmer et al., 2013, 2016). Nevertheless, nowadays a great variety of combinations of modalities are studied, including smell-color (e.g., Demattè, Sanabria, & Spence, 2006; Gilbert et al., 1996; Maric & Jacquot, 2013), shape-taste (e.g., Spence & Deroy, 2014; Spence & Ngo, 2012; Velasco et al., 2015; Velasco, Woods, Marks, et al., 2016; Velasco, Woods, Petit, et al., 2016) or touch-sound (e.g., Guest et al., 2002; Klatzky & Lederman, 2010; Occelli et al., 2011), to only name a few.

3.1. OVERT REPORT METHODS OF COLOR-RELATED ASSOCIATIONS

3.1.1. SYNESTHESIA

Identification of grapheme-color synesthetes relies on two characteristics of synesthesia: its consistency over time and its idiosyncrasy. As such, earliest evaluations of synesthesia consisted in asking participants to verbally report the color experience that each grapheme produces (Simner et al., 2005, 2006). Participants were then asked to repeat the operation a few days/weeks/months apart, to test for the consistency of their experience over time (Simner et al., 2006). Synesthetes appeared to be able to show a level of consistency between testing sessions much higher than controls, even when the retest happened six months later in synesthetes and only two weeks later in controls (Simner et al., 2006). This verbal reporting method comes with the limitation that the synesthetic experience is often a very precise color rather than a general color category, therefore making it unlikely that the wording across testing sessions would be the same, requiring subjective judgement from an external observer to assess whether the two colors described are similar enough or not.

Computerized sampling of the synesthetic experience made this subjective evaluation obsolete. Here, participants are asked to select from an on-screen color picker the precise color they experience (Eagleman et al., 2007). The participants report their experience for each grapheme three times in a random order, without a gap between the first two and last repetitions. Each color response corresponds then to a specific location in a given color space (RGB color space in the case of Eagleman et al., 2007). Euclidean distance calculation allows to measure the distance, and therefore the consistency, between each response for a given grapheme. An average Euclidean distance of 1 across graphemes in the RGB color space has therefore been attested as a threshold to distinguish between synesthetes and controls (Eagleman et al., 2007). The choice of color space and consistency threshold have later been reevaluated

(Rothen, Seth, et al., 2013) determining that the Euclidean distance in the CIELuv color space gave better specificity and sensitivity at a 135.3 threshold. Furthermore, Carmichael and colleagues (2015), confirmed that no gap between testing sessions still leads to reliable results. Lastly, Simner and colleagues (2009) demonstrated that superior memory capacities, in non-synesthete children, was not enough to obtain a consistency score below the synesthesia threshold.

Eagleman and colleagues (2007)'s consistency threshold paradigm is still the tool the most widely used for identifying color-related synesthetes. Current calculation methods allow to correctly classify 90% of the synesthetes who take the test (sensitivity) and 94% of the non-synesthetes (specificity) (Rothen, Seth, et al., 2013).

3.1.2. CROSS-MODAL CORRESPONDENCE

Color associations have been studied in the general population for stimuli such as emotion (e.g., Jonauskaite et al., 2020), music (e.g., Hamilton-Fletcher et al., 2017), smell (e.g., Demattè, Sanabria, & Spence, 2006), shape (e.g., Albertazzi et al., 2013), taste (see Spence, 2019 for review), temperature (see (Spence, 2020) for a review), touch (e.g., (Slobodenyuk et al., 2015), etc. These studies however did not all use the same method to probe overt color answers from their participants. Studies grounded in the synesthesia literature, which had the objective to evaluate whether color association patterns witnessed in synesthetes could also be found in the general population, adopted a paradigm similar to the one used in early synesthesia screenings, by asking participants to produce color terms in response to given stimuli, such as emotion words (Sutton & Altarriba, 2016) or graphemes (Rouw et al., 2014; Simner et al., 2005; van Leeuwen et al., 2016) or weekdays (Rouw et al., 2014).

Cross-modal correspondence research on the other hand has opted for a variety of paradigms to sample color associations for various types of stimuli and can be divided into three main types: those that offered pre-selected colors for participants to choose from, those that extended the color options by providing a partial color space, and finally those that presented participants with a full color space to freely navigate.

3.1.2.1 Pre-selected colors paradigms

Paradigms comprising of pre-selected colors imply that decisions need to be made by the researchers regarding which color options will be made available for the participants to choose from. This involves making decisions concerning the total number of colors that will be featured (e.g., should three or 40 colors be available?), which color categories will be displayed (e.g., should Berlin and Kay (1969)'s 11 focal colors be chosen or would three primary colors be enough?), which hue, chroma and lightness values should be selected for each color (e.g., if the color blue has been chosen by the researcher, should it be a dark blue or a light blue?), and finally, how many varieties of each color category should be featured (e.g., should there be only one or 10 different types of blue?).

In practice, the number of pre-selected colors offered has ranged from as few as three colors (Jacobsen, 2002; Jacobsen & Wolsdorff, 2007), to up to 120 colors (Kim, 2013).

The type of colors pre-selected varies from one study to the other. Studies using only three colors have selected the primary colors red, blue and yellow (Jacobsen, 2002; Jacobsen & Wolsdorff, 2007), and when opting for a forth color, green was added, in order to offer the psychological primary colors (Chen, Tanaka, Namatame, et al., 2016; Morgan et al., 1975). However, the rational for pre-selecting four colors has also been based on the opposite color pairs black/white and red/green (Spector & Maurer, 2008).

Deciding to extend the number of colors does not necessarily result in the decision to offer both primary and secondary colors. As such, Spector & Maurer (2011) offered seven colors including the four psychological primary colors red, green, blue and yellow, and added black, white and brown.

In fact, the pre-selection of colors does not follow any set rule. Three different studies that offered nine pre-selected colors all proposed red, yellow, pink, brown and black, but the remaining four colors varied from green, blue, purple and gray (Boyatzis & Varghese, 1994) to green, blue, purple and orange (Burkitt & Sheppard, 2014), or even light green, dark green, light blue and dark blue (Zentner, 2001).

While Mok and colleagues (2015) made the choice of featuring each 11 Berlin & Kay (1969) focal colors (black, blue, brown, green, grey, orange, pink, purple, red, and yellow), Hemphill (1996) featured every Berlin & Kay (1969) focal colors except for orange. Demattè, Sanabria, & Spence (2006) chose to remove both black and white and included turquoise instead, while Jonauskaite and colleagues (2020), on the other hand, kept the 11 Berlin & Kay (1969) focal colors and added turquoise.

Overall, little justification is provided regarding the choice of pre-selected colors and why other were excluded. While Berlin & Kay (1969)'s focal colors are often cited, they are not necessarily strictly followed. Others also stray away from those focal colors and offer a variety of colors reflecting rather an idea of gradient, such as white, red, red-orange, orange, yellow-orange, yellow, yellow-green, green, green-blue, blue, blue-violet, violet, red-violet, black (Freeman, 2020).

Moreover, on top of differing greatly in the number of color options, having several studies offering the same color category, say green, does not imply that the specific color pre-selected will be similar across studies. When some may choose a light vivid green and others pick a darker, muted one. Here again, for most studies, little justification is provided regarding the precise pre-selected colors.

In order to more reliably sample the general population's experience, some studies have adopted a paradigm where pre-selected color categories are offered in several shades.

Some researchers extended the list of colors by creating a more detailed gradient of colors (Maric & Jacquot, 2013; Nehmé et al., 2016) or by selecting some hues and manipulating their levels of lightness (Dreksler & Spence, 2019; Lin et al., 2021) and chromaticity (Xiuwen et al., 2018). However, it is more common to simply select colors from a pre-established color space, such as the Natural Color Space (Albertazzi et al., 2013, 2015; Chen, Tanaka, Matsuyoshi, et al., 2015; Chen, Tanaka, Namatame, et al., 2015; Dadam et al., 2012; Malfatti, 2014; Palmer & Schloss, 2010), Munsell chips (de Valk et al., 2017; Wright et al., 2017), the HSL color space (Shin et al., 2020), the IRI Hue and Tone System (Kim, 2013) or reusing the 37 colors from the Berkeley Color Project (Griscom, 2015; Levitan et al., 2014; Malfatti et al., 2014; Palmer et al., 2013; Ren et al., 2012; Schloss et al., 2020). Such paradigms have offered between 24 and 120 pre-selected colors to choose from.

Extending the number of pre-selected colors is a good way to sample more subtle aspects of color-related cross-modal correspondence, however, the use of a variety of color spaces to choose from means that the exact same colors are not available in all studies. Furthermore, here again, little justification is provided regarding why a certain color space was favored over the other ones, apart from consistency between studies.

3.1.2.2 Partial color space paradigms

Studies offering participants the possibility to report their preferred color associations using partial color spaces opted for such a paradigm rather than a full color space for hypothesis testing reasons. Specifically, a color is the association of a hue, a chromaticity value, and a lightness value. However, the 11 focal colors identified by Berlin & Kay (1969) are not just different hues spread to form a uniform color circle, and where varying chromaticity and lightness allows to obtain different shades of the same color. For example, decreasing the lightness value of focal orange creates brown, meaning that both brown and orange have the same hue values. Similarly, decreasing the lightness value of focal yellow creates an olive-green color. Moreover, each focal color does not have the same chromaticity and lightness values. For example, in the CIELuv color space, focal green has a lightness value of 50 and chromaticity of 35 while focal yellow has a lightness value of 76 and chromaticity of 70 (Witzel & Franklin, 2014).

As such, when participants report that a certain stimulus is associated to the color yellow, it denotes a certain hue value, but also implies that it is associated to both high chromaticity and lightness. It is therefore complex to rule out that the association to yellow is due to a preference for this specific hue, rather than for any high chromaticity and/or high lightness color.

It has been found that a large proportion of the population associate pitch frequency to lightness, where higher pitches are associated to brighter lights (Hubbard, 1996; Marks, 1987). This led Hamilton-Fletcher and colleagues (2017) to opt for a partial color space paradigm, where the lightness value was the same across all colors, in order to investigate pitch-hue and pitch-chromaticity associations specifically.

3.1.2.3 Full color space paradigms

Full color space paradigms are the ones that offer the most freedom to the participants, who are therefore not confined to pre-selected colors that may not reflect their actual preferred choices and are able to fine-tune the hue, chromaticity, and lightness values. Several color spaces exist and the choice of a specific color space over the others differs between studies. A total of 1565 Munsell color chips (Gilbert et al., 1996) or the RGB color space (Ward, Huckstep, et al., 2006) have been used in earlier studies. However nowadays, the most commonly used color spaces are the HSV (Saluja & Stevenson, 2018; Slobodenyuk et al., 2015; Wang & Li, 2022) and CIELab (Delazio et al., 2017; Lindborg, 2014; Lindborg & Friberg, 2015; Ludwig & Simner, 2013) ones.

The RGB color space is an additive one, meaning that any color can be created by just mixing certain amounts of red, green and blue. The value of red, green and blue can range from 0 to 255, with pure red corresponding to RGB(255, 0, 0), pure green RGB(0, 255, 0) and pure blue RGB(0, 0, 255). It is commonly used for displaying colors on television and computer monitors using red, green, and blue cathodes.
The Munsell, HSV and CIELab color spaces are on the other hand built around the three components of color: hue, chromaticity, and lightness.

The Munsell color space starts with five main hues (red, yellow, green, blue, and purple) and five intermediate hues (red-yellow, yellow-green, green-blue, blue-purple and purple-red). Ten steps were then inserted between each of the 10 hues, resulting in a 100-step hue circle. The lightness component consists of 10 perceptually uniform steps and indicate the amount of white/black in the color and is commonly represented as an axis perpendicular to the hue circle. The chromaticity component represents the amount of gray in the color and therefore represents the distance from the lightness axis. Chromaticity in the Munsell color space is also perceptually uniform and incremented in equally spaced steps. Since completely muting the most vivid red requires more addition of gray than muting the most vivid blue, the most vivid red color is further away from the lightness axis than the most vivid blue in the Munsell color space. As such, the number of chromaticity steps vary depending on the hue (Cleland, 1921). The Munsell color space is commonly used to measure color pigments. Its use in science therefore mostly involves printing out the color stimuli.

The HSV color space stands for Hue, Saturation (chromaticity), and Value (lightness), and is a transformation of the RGB color space into the three components of color. Similar to the Munsell color space, hues are organized in a circle, with pure red-RGB(255, 0, 0) at 0°, pure green-RGB(0, 255, 0) at 120° and pure blue-RGB(0, 0, 255) at 240°. Lightness is here again an axis perpendicular to the hue circle, ranging from 0 (white) to 1 (black). While in the Munsell color space chromaticity varies as a function of the amount of gray in the color, in the HSV color space chromaticity varies as a function of the amount of white in the color. Similar to the RGB color space, its most common use is in the domain of broadcasting.

The CIELab color space is composed of a hue circle built using two axes perpendicular to each other ranging from -100 to 100. Namely, the *a* axis ranges from green to red, and the *b* axis ranges from blue to yellow. Converting the cartesian coordinates (*a, b*) into polar coordinates (r, θ) allows to compute the hue value θ in degrees and the chromaticity value r as a distance from the point (0, 0) of the *a* and *b* axes. Lightness is here again represented as an axis perpendicular to the hue circle, ranging from 0 to 100, representing the amount of gray in the color. The CIELab color space has been designed to be perceptually uniform, meaning that the mathematical distance between two points in the CIELab color space reflects the subjective difference perceived by human vision (International Organization for Standardization, 2018).

The differences in how the various color spaces are built mean that different studies investigating the same cross-modal correspondence but using different color spaces may produce different results. Chromaticity does not have the same properties in the HSV and CIELab spaces for example, with the former one being a measure of the amount of white in the color and the latter of the amount of gray (white+black) in the color. Similarly, a hue difference of 180° in the CIELab space for two different stimuli implies that they are associated to perceptually opposite colors. In the HSV space on the other hand, it is difficult to infer perceptual aspects of color responses.

3.2. INDIRECT METHODS OF COLOR-RELATED ASSOCIATIONS

3.2.1. SYNESTHESIA

An early preoccupation of synesthesia researchers was to find out whether the synesthetic experiences could be observed using indirect methods. While the consistency score method presented above relies on overt reports from synesthetes, an indirect sampling method would further demonstrate the genuineness of the experiences, and also indicate which cognitive processes are involved and/or affected by synesthesia. It would also demonstrate that synesthetes do not use any overt strategy to get classified as synesthetes during testing.
To reach this goal, instead of making use of the consistency and idiosyncrasy aspects of synesthesia, the focus has been put on the automatic and perceptual properties of the synesthetic experience.

3.2.1.1 Pop-out effects

Grapheme-color synesthetes cannot help themselves perceiving specific colors whenever presented with given graphemes. Furthermore, two graphemes that look very similar (e.g., A/4, S/5, O/Q) may for a given synesthete look very different colorwise. This is the basis for experimental paradigms that aimed to demonstrate that synesthetes performed better than controls in visual discrimination tasks.

Visual search tasks require participants to locate a target stimulus among distractors (Treisman & Gelade, 1980). It has been observed that, when the target was physically in a color different from the distractors, a pop-out effect occurs, meaning that the target is immediately perceived, and increasing the number of distractors does not make the response time longer. It was therefore formulated that in such visual search arrays, the processing of stimuli occurs in parallel, and that attention to stimulus is not necessary for distinguishing the target from distractors (Treisman & Gelade, 1980). On the other hand, when the target differs from the distractors due to a conjunction of features, such as shape and color (e.g., finding the red 2 among green 2s and red 5s), response times get slower as the set size increases. It has been proposed by Treisman & Gelade (1980) that this is due to stimuli now being processes in a serial manner, with attention needing to be directed to stimuli in order to locate the target.

In a visual search task requiring to locate a target grapheme among distractor graphemes, a grapheme-color synesthete was able to respond faster than controls and showed a reduced set size effect (Palmeri et al., 2002). Critically, the target and distractors were different in their synesthetic colors but were all displayed in black. These results are in line with early observations that visual search for an oddly colored target are fast and resistant to set size (Treisman & Gelade, 1980), confirming according to the authors that grapheme-color synesthesia involves the perception of real colors.

In another visual search task, which featured a one-second display of several target graphemes arranged as a shape among distractors (Ramachandran & Hubbard, 2001a), two grapheme-color synesthetes managed to identify the shape formed by the target graphemes in 81% of the trials, while controls could do so in only 59% of the trials.

Finally, it is also possible to cancel out the pop-out effect witnessed in synesthetes by presenting a visual search array against a background in a color congruent to the target stimulus' color (Smilek et al., 2001).

The studies presented above make a convincing case that grapheme-color synesthetes' experience is genuine and similar to real color perception. However, they suffer from a severe limitation. All these studies were run on a single or two synesthetes only. In order to be able to make strong claims that can be generalized to the whole grapheme-color synesthete population, studies with stronger statistical power needed to be conducted.

When attempting to replicate the previous findings on the visual search task with a group of 14 synesthetes and 14 controls, the expected pop-out effect occurred when stimuli where physically colored in both groups (Edquist et al., 2006). However, relying only on the synesthetic colors, the synesthete group reaction times increased as a function of set size, opposite to what had been found in the original case study (Palmeri et al., 2002). Similarly, when testing a group of 13 synesthetes and matched controls, the results of Ramachandran & Hubbard (2001a)'s shape detection study run on only one synesthete could not be replicated (Rothen & Meier, 2009). Moreover, when testing whether target detection would be facilitated when its synesthetic color was different from the distractors, but hindered when its synesthetic colors was similar to at least one of the distractor, no effect was found in a group of seven synesthetes and controls (Gheri et al., 2008).

The pop-out effect due to the synesthetic colors found in earlier case studies should indicate that all items of the visual search array undergo parallel processing in synesthetes (Treisman & Gelade, 1980), meaning that the synesthetic color perception is pre-attentional, i.e., occurring without identifying the grapheme. It seems however not to be the case. When testing a group of 36 synesthetes and controls, the better performance in the synesthete group found by Ramachandran & Hubbard (2001a)'s case study could be replicated (Ward et al., 2010). However, the pop-out effect was not phenomenologically reported by most of the participants, indicating that serial processing does occur in synesthetes performing a visual search task. Indeed, synesthetes did not show a set size effect when the target stimuli was placed up to 6° away from the fixation point (Laeng et al., 2004). Nevertheless, passed this distance, reaction time increased as a function of set size, denoting an attentional, serial processing (Laeng et al., 2004). Similarly, five out of six synesthetes were faster at identifying a target among distractors in the visual search task than controls when viewing black stimuli (Hubbard, Arman, et al., 2005). However, they were slower than controls who saw the stimuli physically colored, indicating that the synesthetic color experience is not completely similar to the perception of a real color. Furthermore, while the presence of a physical color in visual memory could guide attention in a visual search task (Carlisle & Woodman, 2011), the synesthetic colors did not appear to be able to produce such an attentional bias (Sørensen et al., 2015). The importance of attention in the synesthetic experience was shown using Navon stimuli, as shown on the right in Fig. 2-2 (Rich & Mattingley, 2003), where participants had to report the displayed color of either the global (the shape of a 5 in Fig. 2-2) or local (the 3s in Fig. 2-2) level of the stimuli. When the attended level was shown in an incongruent color to the synesthetic one, the color naming time increased compared to when it was shown in a congruent color. However, incongruency of the unattended level had significantly less impact on the color naming time. The attentional aspect of synesthetic color perception was further demonstrated using whole and partial report paradigms (i.e., participants are required to report every item, or only a certain category of items, briefly presented on the screen), whereby stimuli presented in a color congruent to the synesthetic color were processed faster and in a larger number (Ásgeirsson et al., 2015).

While appearing promising in early case studies, visual search paradigms do not seem efficient enough to distinguish synesthetes from controls. Particularly, too great variations in behavioral performances and phenomenological reports happen across synesthetes (Rothen & Meier, 2009; Ward et al., 2010) to be able to reliably sort synesthetes from controls. Overall, it seems that pop-out effects due to synesthesia are not as evident as originally thought. For example, Miozzo & Laeng (2016) reported that out of two synesthetes who both describe projector-like synesthetic experiences, only one showed a pop-out effect. The lack of participants in early studies may have caused false positives (Rothen & Meier, 2009), as the pop-out effects implies that the synesthetic experience is pre-attentional, which does not appear to be the case (Ásgeirsson et al., 2015; Laeng et al., 2004; Rich & Mattingley, 2003).

3.2.1.2 Grouping effects

It is not rare for synesthetes to have several graphemes that share similar colors (see digits 4/7, 5/9 for synesthete AR and digits 2/5 for synesthete AZ from Fig. 2-1). Some researchers have therefore tried to evaluate whether similarities between synesthetic colors would be stronger than the physical similarities of those graphemes. In order words, do graphemes that look different (e.g., X and I) would be judged more similar by synesthetes than controls when their synesthetic colors are similar? And inversely, do graphemes that look similar (e.g., A and 4) be judged more different by synesthetes than controls when they have very different synesthetic colors?

In a case study (Ramachandran & Hubbard, 2001a) involving two synesthetes, digits were grouped based on the similarity of their synesthetic colors, rather than on the similarity of their physical shapes (e.g., red 3s were grouped with red 7s, rather than green 8s).
When asked to spatially organize graphemes based on similarity, without mentioning that the judgement was to be made based on synesthetic colors, a group of 20 synesthetes grouped stimuli with similar synesthetic colors closer to each other, and stimuli with different synesthetic colors further apart (Gravener et al., 2022). The results negatively correlated with scores on the overt report consistency test (Eagleman et al., 2007) and the projector/associator distinction did not cause different results. However, 12 of the 20 synesthetes reported consciously making the similarity judgement based on the synesthetic colors. The paradigm could still have potential as an indirect method to sort synesthetes from non-synesthetes, provided results can be replicated and manage to show sensitivity/specificity equal to the overt report method.

3.2.1.3 Competition with real colors

One of the most famous and widely used cognitive task that relies on the automaticity of processes is the Stroop task (Stroop, 1935). In the original Stroop paradigm, participants are presented with a list of 100 color words, all written in an incongruent ink color (e.g., “red” written in blue ink). An identical stimuli list written now in black, and a list consisting only of 100 colored patches were used as baseline conditions. Participants were alternatively asked to name the ink color of the colored-words list, to name the ink color of the colored-patches list, to read the color names of the colored-words list and to read the color names of the black-words list. Participants took longer to name the ink color of the colored-words list than of the colored-patches list. They, however, took the same amount of time to read the color names of the colored-words list and of the black-words list. These two tasks showed that the reading process interferes with the color naming one, but not the opposite, due to the automaticity of reading and the non-automaticity of color naming.

Several studies made use of the rational of the Stroop task to demonstrate the automaticity of the synesthetic experiences (Dixon et al., 2000; Mills et al., 1999; Odgaard et al., 1999; Wollen & Ruggiero, 1983). Mills and colleagues (1999) and Dixon and colleagues (2000) each presented a digit-color synesthete with digits in colors congruent and incongruent to their synesthesia. As baseline condition, Dixon and colleagues (2000) used colored squares, while Mills and colleagues (1999) selected both colored circles and black digits. In both studies, the synesthete participant took longer to name the ink color in the incongruent condition, compared to the congruent and baseline conditions, showing an interference effect due to the automatic synesthetic experience. Dixon and colleagues (2000)'s control non-synesthetes, on the other hand, showed similar reaction times across all three conditions, due to their lack of automatic synesthetic experiences. When asked to read the digit stimuli in the incongruent, congruent and black baseline conditions, response time did not differ (Mills et al., 1999).

Increasing the number of participants to 15 synesthetes and 15 controls, a similar congruency effects was found in the synesthete group but not in controls (Mattingley et al., 2001). The authors also showed that in a block-paradigm (i.e., congruent and incongruent trials are shown separately), synesthetes were faster than controls in the congruent condition, and slower than controls in the incongruent condition, denoting both a facilitation and an interference in synesthetes. In an intermixed paradigm however, synesthetes and controls were equally fast in the congruent and neutral conditions, showing no facilitation effects, meaning that the congruency effect found in synesthetes was now only due to interference from the incongruent condition (Mattingley et al., 2001). Those results showed that while interference effects can be attested across paradigms, facilitation effects are sensitive to paradigm choices.

Congruency effects on an adapted version of the Stroop task also appeared when testing for pitch-color synesthesia at the group level (Ward, Huckstep, et al., 2006).

Dixon and colleagues (2004) found that projector synesthetes had larger congruency effect and faster response times when they were asked to name the color of the grapheme presented on the screen than when asked to retrieve the synesthetic color of the grapheme. Associator synesthetes, on the other hand, showed an opposite pattern. Dixon and colleagues (2004) interpreted this opposite pattern between groups as due to projectors having more automatic synesthetic experiences than associators, as well as the processes involved in the synesthetic color experience being more automatic than the ones leading to the experience of the stimuli color in projectors. Nevertheless, several studies have since then failed to find the pattern claimed by Dixon and colleagues (Hancock, 2006; Laeng et al., 2011; Levy et al., 2017; Mattingley et al., 2001; Mattingley & Rich, 2004; Nikolić et al., 2007).

3.2.1.4 Priming effects

Priming paradigms have also been used to demonstrate the automaticity of the synesthetic experience, once again mostly in the context of grapheme-color synesthesia. In a priming paradigm a first stimuli, the prime, influences the response to the second stimuli, the target. As such, when asked to name the color of a target color patch, a grapheme-color synesthete was slower when it followed an incongruent number prime than a congruent one (Dixon et al., 2000). Interestingly, the number prime was not directly show on the screen. Instead, it was the mental representation of an arithmetic problem shown on the screen. These results indicated that the conceptual level of the grapheme was enough to automatically induce a synesthetic experience. Mattingley and colleagues (2001) presented grapheme-color synesthetes and controls with alphanumeric characters as primes followed by a mask and a target color patch. Participants were asked to name the color of the target. On each trial, the synesthetic color of the prime could be either congruent or incongruent to the color of the target. They also manipulated the duration of the prime and found that at short durations (26ms and 58ms) the prime incongruency did not cause interferences with the target, while it did at a 500ms presentation. Controls on the other hand showed interference in none of the conditions. They also conducted a control experiment where both the prime and target were letters, either congruent or incongruent, and asked participants to name the target letter. They found an interference in both groups at 26ms and 58ms prime duration, showing that the primes where still processed but unconsciously. They concluded that conscious awareness of a prime causing a synesthetic experience was necessary to interfere with the target. Blake and colleagues (2005) though argued that an interference may have also been present in the synesthetic priming task, but as the color naming process is more variable than the letter naming one, the lack of power may have not allowed to find significant differences. Nevertheless, when Mattingley and colleagues (2006) manipulated attention load, is a priming paradigm, the high attention load condition reduced the priming effect compared to the low attention load condition. The high attention load condition required indeed participants to direct their attention away from the synesthetic inducer prime.

Repeating Mattingley and colleagues (2001)'s paradigm but manipulating this time the duration between prime and target presentation and maintaining the duration of the prime to 200ms, Spruyt and colleagues (2009) found that interference occurs when both the prime and targets were presented at the same time, when the target was presented immediately after the prime, and when a 800ms gap occurred between prime and target presentation. They concluded that the concurrent experience occurs automatically as soon as the inducer has been consciously perceived, as interference occurred when both the prime (synesthetic inducer) and target were presented simultaneously. Their result should nevertheless be taken carefully, as they report significant planned post-doc comparisons for a non-significant interaction of congruency and stimulus onset asynchrony, consisting of right-tailed tests not corrected for multiple comparisons. With two-tailed testing and appropriate correction, both the simultaneous and directly successive presentations are above the significance threshold, potentially due to a lack of power.

Some studies have also used priming paradigms in order to test the directionality of synesthesia. While synesthesia is often described as unidirectional (Grossenbacher & Lovelace, 2001; Mills et al., 1999), where an inducer causes a concurrent experience, but the concurrent rarely causes the experience of the inducer, several priming studies have challenged this assumption. Weiss and colleagues (2009) found that in 10 grapheme-color synesthetes the concurrent colors could act as a prime that influenced the letter chosen to complete a partially presented word. Gebuis and colleagues (2009b) found also that in 19 grapheme-color synesthetes the same magnitude of interference occurred in a target naming task both when a number served as the prime and a color as the target, and when a color served as the prime and a number as the target. The same effect was found when the numbers were presented auditorily (Paffen et al., 2015), further showing that the synesthetic association between digits and colors occurs at the conceptual level, as previously shown by Dixon and colleagues (2000). This is in line with larger N400 due to incongruency in a priming paradigm in which either a word, a grapheme or a color patch was used as the final element of a sentence (e.g., “The is sky is blue/6/🟦”) to form a semantically congruent or incongruent sentence ending (Brang et al., 2008; Brang, Kanai, et al., 2011).
Gebuis and colleagues (2009b) also found a numerical distance effect (i.e., the priming effect increases when the prime and target denote items numerically closer) only when the color served as a prime and the number as a target, which they further interpreted as evidence for bidirectionality of the synesthetic experience, where both types of prime (i.e., numbers and colors) conjure a synesthetic experience. They however do not discuss whether any type of priming distance effect can even be expected to happen when participants are asked to produce a color word (which has no intrinsic magnitude value) compared to a number (which have an intrinsic magnitude value). Indeed, letters, which despite having a linear ordered organization have no intrinsic magnitude value, do not produce a priming distance effect (Van Opstal et al., 2008). Together those results suggest that a priming distance effect was unlikely to occur in Gebuis and colleagues (2009b)’s number-color priming task, where the magnitude information from the prime has no effect on the color naming task as it does not involve any magnitude processing.

Priming studies show congruency effects at the group level due to the synesthetic experience, however they are not a method commonly used to index synesthesia itself, but rather to investigate its underlying mechanisms. While adapting the Stroop task to synesthesia seems an efficient manner to detect synesthesia at the group level, at the individual level a lot of fluctuations between participants exists (Mattingley & Rich, 2004), rendering the paradigm difficult to use to sort out synesthetes from controls individually.

3.2.2. CROSS-MODAL CORRESPONDENCE

As previously mentioned, cross-modal correspondence differs from synesthesia in that it is not conscious. This means that when asked what color fits best a certain stimulus, individuals would feel that they are just providing a random answer. It is only when looking at the sum of answers from a large group of individuals that patterns start appearing.

Similarly to synesthesia, cross-modal correspondence researchers have attempted to show that those experiences could be sampled indirectly, in order to further show their genuineness and to understand their underlying processes, but also because it would be more practical to unveil unconscious experiences.

3.2.2.1 Stroop effects in cross-modal correspondence

The Stroop effect (Stroop, 1935) posits that an automatic process (i.e., reading) will interfere with a non-automatic one (i.e., naming ink color). The degree to which cross-modal correspondence is automatic is not clear and it has been argued that different types of cross-modal correspondence may vary in automaticity depending on the stage of human development they arise in (Spence & Deroy, 2013).

Past studies have so far not succeeded in finding a congruency effect for color-related cross-modal correspondences, such as pitch-color (Ward, Huckstep, et al., 2006) or facial emotion-color (Ikeda, 2020).

It should be noted though that running a Stroop task for color-related cross-modal correspondence is quite difficult. In the case of pitch-color cross-modal correspondence, the color reported for each pitch by each participant is not as precise as the ones reported by synesthetes, probably due to the lack of conscious experience (de Thornley Head, 2006; Ward, Huckstep, et al., 2006). For this reason, building a congruent condition is a complex task. Ikeda (2020) has opted for a red-angry/green-happy mapping across participants based on past findings, but Ward and colleagues (2006) found themselves forced to use the pitch-color pairs from matched synesthetes for each controls due to the lack of literature regarding pitch-color cross-modal correspondence. As such, controls were possibly never in a position of being tested for their cross-modal correspondence given that none of the condition may have truly been congruent. When testing for pitch-elevation cross-modal correspondence using an adapted Stroop paradigm, Melara & O'Brien (1987) found a congruency effect, but importantly, this congruency effect relied entirely on a facilitation in the congruent condition, the incongruent condition causing no interference. Critically, when matching a group of controls' stimuli to a synesthete's experience of pitch-elevation synesthesia, Linkovski and colleagues (2012), found no congruency effect in their control group. The synesthete's pitch-elevation mapping was though not extremely different from what had been found in cross-modal correspondence (i.e., higher pitch located upward, and lower pitch located low). Having matched the control participants' stimuli to the synesthete's stimuli may have hindered the facilitation effect previously found from pitch-elevation cross-modal correspondence ((Melara & O'Brien, 1987). Although Ward and colleagues (2006) found that while synesthesia and cross-modal correspondence shared similarities when it comes to pitch height-lightness or timber-chromaticity, the pitch-color mappings may vary between phenomena. More particularly, while cross-modal correspondence leads to making color choices primarily by mapping pitch height to lightness, synesthetes did so only in the blue dimension of the RGB color space (de Thornley Head, 2006). For these reasons, Stroop effects for pitch-color cross-modal correspondence may have failed to be found due to methodological decisions.

3.2.2.2 Implicit association task (IAT)

The Implicit Association Task (IAT) was developed as a measure of unconscious associations (Greenwald et al., 1998, see however Arkes & Tetlock, 2004; Blanton et al., 2009; Blanton & Jaccard, 2006; Gawronski et al., 2007; Oswald et al., 2013 for discussions regarding the limitations of the method). It supposedly measures implicit associations between concepts, by asking participants to sort items into two possible categories. It starts by asking participants to sort items into two sets of two categories (e.g., Set 1: food or clothes? Set 2: cheap or expensive?). Then, the items are asked to be categorized according to a conjunction of Set 1 and Set 2 (food and cheap or clothes and expensive?) with pairings alternated (food and expensive or clothes and cheap?). Response time differences in the categorization of conjunction attribute should then highlight implicit conceptual associations in participants (e.g., wagyu beef is categorized faster as food and expensive than food and cheap).
The idea of unveiling unconscious associations made IAT a popular choice for assessing cross-modal correspondence (Parise & Spence, 2012).

The IAT has been used to assess color-related cross-modal correspondences, such as temperature-color associations (hot-red/cold-blue; Ho et al., 2014), shape-color associations (no significant results from Makin & Wuerger, 2013; circle-red/triangle-yellow/square-blue found by Chen, Tanaka, & Watanabe, 2015) or smell-color associations (strawberry-pink/spearmint-turquoise; Demattè, Sanabria, & Spence, 2006).
IAT comes, however, with limitations for testing cross-modal correspondence. First, it is based on a two-category sorting task, meaning that it works best for assessing dichotomous pairings (e.g., hot vs cold). Second, it highlights only the pairings that are being tested. Taking shape-color associations as an example, Makin & Wuerger (2013) aimed at assessing whether the shape-color associations claimed by Kandinsky (1912) existed in the general population (circle-blue/triangle-yellow/square-red). Therefore, congruent and incongruent conditions were built around those pairings, meaning that pairs such as triangle-yellow/square-blue vs. triangle-blue/square-yellow were never tested. This means that IAT is strongly hypothesis-driven, and mainly aims at confirming or disproving associations found, for example through overt reports. Third, IAT does not always manage to detect associations found with

overt reports. For example, while deaf Japanese participants overtly reported circle-red/triangle-yellow/square-blue and green associations, the IAT failed to find any bias for such pairings (Chen, Tanaka, Namatame, et al., 2016), leading the authors to hypothesizes that shape-color associations may be less strong in deaf than hearing participants. Forth, criticism has been largely made towards the IAT both regarding methodological flaws and the psychological processes truly implicated, but for the purpose of probing cross-modal correspondences, the most relevant limitation might be that IAT may not be tapping into unconscious processes as hoped for. It is seems in fact that participants are able to predict their IAT scores (Hahn et al., 2014). This would unfortunately mean that IAT is not able to unveil more associations than overt reports can.

Overall, when looking at intuitive associations (e.g., hot-red/cold-blue), IAT supports the associations with little surprise, however, when probing less straightforward pairings (e.g., shape-color), IAT provides conflicting results between studies (Chen, Tanaka, Namatame, et al., 2016; Chen, Tanaka, & Watanabe, 2015; Makin & Wuerger, 2013) and also compared to behavioral data (Chen, Tanaka, Namatame, et al., 2016).

3.2.2.3 Speeded classification task

Garner & Felfoldy (1970) designed an experiment in which stimuli varied along two different dimensions of the visual modality (e.g., lightness and saturation) and participants were asked to classify each stimulus along only one of those two dimensions. In a baseline condition, the irrelevant dimension was held constant (e.g., lightness values were constant, and saturation varied), in a correlated condition the irrelevant dimension varied together with the relevant one (e.g., lightness and saturation could be either positively or negatively correlated), and in an orthogonal condition the two dimensions could be combined in all possible pairs. Dimensions for which performances were poorer compared to baseline in the negatively correlated and orthogonal conditions and better in the positively correlated condition were defined as “integral dimensions” which are processed holistically (e.g., lightness and saturation), while for “separable dimensions” (e.g., circle size and angle diameter) no difference occurs compared to baseline (Garner, 1976).

Speeded classification tasks have since then been used across modalities, mostly between the visual and auditory ones. Bernstein & Edelstein (1971) asked participants to report the location of a target on the screen (high or low) while different pitch heights were used as irrelevant stimuli. A congruency effect was found, which has since then been replicated (Ben-Artzi & Marks, 1995; Evans & Treisman, 2010; Melara & O’Brien, 1987; Patching & Quinlan, 2002), indicating an association between pitch height and physical elevation.
A variety of cross-modal associations have been investigated using a speeded classification task (Marks, 2004), such as pitch height-lightness associations (Marks,

1987; Martino & Marks, 1999; Melara, 1989), pitch-motion (Clark & Brownell, 1976), pitch-size (Evans & Treisman, 2010; Gallace & Spence, 2006), pitch-roundedness (Marks, 1987), loudness-brightness (Marks, 1987). Evans and Treisman (2010) further found that associations between pitch and size, pitch and physical elevation, and pitch and spatial frequency were bidirectional using a speeded classification task.

However, some cross-modal pairs failed to produce congruency effects in the speeded classification task (pitch-color hue; Bernstein et al., 1971, pitch-contrast; Evans & Treisman, 2010, loudness-lightness; Marks, 1987). Direct report methods have nevertheless shown a tendency for high pitches to be associated with orange/yellow hues and low pitches with blue hues (Hamilton-Fletcher et al., 2017). A critical reason for failure to find congruency effects in the speeded classification task might therefore be that Bernstein and colleagues (1971) tested the wrong pairs, namely high-blue and low-red pairs.

Finally, Gallace and Spence (2006) and Bernstein and colleagues (1971) found that the congruency effect disappeared during block presentation for high pitch, low pitch and no sound trials, meaning when the input from the irrelevant dimension did not vary between trials. Interestingly, in the context of grapheme-color synesthesia, Mattingley and colleagues (2001) found an opposite pattern, where facilitation beneficiated from a block presentation.

3.3. EVALUATION OF THE VARIOUS METHODS

The overt reporting method (Eagleman et al., 2007; Ásgeirsson et al., 2015) has managed to impose itself as the standard in the color-related synesthesia literature.

The task though comes with some limitations for synesthetes. They can for example only report one color for each stimulus, even though it is not rare for inducers to have multiple colors at the same time. Similarly, participants are limited to the colors present in the color space. As such neon or metallic colors can only be reported by selecting a color that feels close enough to the truly experienced one. Finally, the “martian colors” that some synesthetes experience, such as a greenish red (Ramachandran & Hubbard, 2005) can simply not be reported.

Nevertheless, Eagleman and colleagues (2007)’s consistency threshold paradigm is a valuable tool to detect color-inducing synesthesia at the individual level, and efforts are being made in order to fine-tune color reporting (Ásgeirsson et al., 2015; Root, 2021).

Despite color-related synesthetes experiencing automatic color perceptions for stimuli that are normally perceived deprived of colors, to this date, no indirect method has been found to reliably identify synesthetes and non-synesthetes at the individual level. While the consistency of experiences over time, on which the overt report method relies, is a key aspect of synesthesia (Grossenbacher & Lovelace, 2001), the automatic and perceptual aspects of the experience, which indirect methods rely on, is less evident to measure precisely. The indirect methods presented above use response times, and accuracy to some extent, as a proxy to evaluate the presence of synesthesia. Reaction time is the delay between the presentation of a stimulus and the response provided by the participant. In the case of visual search tasks, the automatic and perceptual aspects of the synesthetic experience were hoped to allow synesthetes to locate the target item(s) faster than controls. In the synesthesia variation of the Stroop task, the automatic aspect of the synesthetic experience was expected to slow ink-naming speed when the stimulus is in a color incongruent to the synesthetic experience, but to make ink-naming easier if the stimulus color corresponds to the synesthetic one. Similarly, in priming tasks the congruency of the prime with the target was expected to speed up responses to the target, while incongruency causes slower responses. Unfortunately, but not surprisingly, those tasks relying on response time are quite inefficient at the individual level. Reaction times can be affected by a vast range of processes, that also vary during the course of a testing session, such as fatigue or arousal, or due to varying cognitive profiles between participants (Baayen & Milin, 2010). For this reason, while Stroop effects are informative at the group level, at the individual level, congruency effects may not always occur (Mattingley & Rich, 2004).

The field of color-related cross-modal correspondences has not had the chance of seeing a standard method of overt report emerge. For this reason, comparison between studies is quite tedious.

Paradigms featuring pre-selected color options are a manner to facilitate statistical analysis, but at the same time, they lack precision when sampling experiences. The studies cited above using pre-selected color options feature the most restricted paradigms, and as such imply strong influences from the researchers on the resulting data. Let us imagine a participant who would instinctively want to associate a given stimuli to the color orange. Their reported color would not reflect their experience if only offered the psychological primary colors red, blue, green, and yellow or if the experimenter took the decision to include all Berlin & Kay (1969) focal colors except orange. In such a situation, it is also difficult to reliably predict the participant's underlying rational for selecting any another of the other colors offered. Would they select the nearest color (red)? Would they select the second most fitting color (possibly blue for this person)? Would they just select a random option due to their preferred choice not being offered? Would they use any sort of strategy to resolve the issue (the stimulus reminds them of a given item, they will therefore select the color of the item)?

Paradigms offering a full color space to choose from limit the involvement of the researchers, but they make data analysis more complex. Variability between data points is much greater when participants can freely choose any shade of blue that exists, rather than being forced to choose a specific one. Nevertheless, full color space paradigms allow to measure the involvement of the different components of color (i.e., hue, chromaticity, and lightness). Unfortunately, such paradigms are still the minority in the literature and the usage of different color spaces limit the possibilities of comparisons between studies.

Indirect methods to sample color-related cross-modal correspondence suffer from the same limitations as the ones involved in the synesthesia literature, namely, response times are subjected to a lot of variations during testing. On top of this, their purpose is to unveil associations that are, in theory, not consciously available to participants. In such a context, the possibilities to reliably sample experiences at the individual level are even more minimal. IAT seems efficient to demonstrate color-related associations, although it seems to work best for “obvious” associations (e.g., cold-blue/hot-red) that may anyway be consciously available for participants to report. The speeded classification task is a good method to indirectly sample cross-modal associations. However, as it relies on congruency of the tested modalities, it requires a priori assumptions regarding the congruent and incongruent pairs, an aspect especially critical when testing color associations, for which cannot objectively be reduced to a two-level dimension, unlike pitch (i.e., high vs low).

3.4. GOAL OF THE THESIS

This chapter presented various manners to sample color-related synesthetic and cross-modal experiences. Overall, synesthesia is better detected at the individual level using an overt report method but is also able to be demonstrated at the group level using a priming task or a variation of the Stroop task. Small sample sizes in early studies investigating advantages in visual search in synesthetes have led to results that mostly failed to be replicated, highlighting the importance, as for the case of imaging studies, to replicate results and test a larger number of participants. Cross-modal correspondence on the other hand suffers from a lack of harmonization in its overt report methods. The Implicit Association Task remains a highly debated method in the field of psychology in general and the speeded classification task is a better tool to confirm associations than unveiling new ones.

The three following chapters report three studies that aimed at replicating past results regarding shape-color correspondences and congruency effects in the grapheme-color synesthesia Stroop.

3.4.1. LOW IDIOSYNCRASY IN SHAPE-COLOR CORRESPONDENCES

Although shape-color associations formally occur at the intra-modal level within the visual modality, recent studies investigating this type of associations were carried within the scope of cross-modal research (Chen & Watanabe, 2020; Dreksler & Spence, 2019) and the presence of sound-shape and sound-color cross-modal correspondence was viewed as an indication that shape-color associations could also exist (Chen, Tanaka, Matsuyoshi, et al., 2015). Most research on synesthesia, commonly defined as a union between senses, has been carried on grapheme-color synesthesia, an instance of intra-modal associations (Marks & Odgaard, 2005), indicating that synesthesia may also occur at the dimension level within sensory modalities, or even at the conceptual level (Chiou & Rich, 2014), rather than at the sensory level. Inversely, intra-modal correspondences are understudied in the general population and overlooking them may bias conclusions regarding associations in the general population (Dreksler & Spence, 2019).

Method-wise, past shape-color correspondence studies only adapted overt report paradigms that offered pre-selected color chips (Albertazzi et al., 2013; Chen et al., 2019; Chen, Tanaka, Matsuyoshi, et al., 2015; Chen, Tanaka, Namatame, et al., 2016; Hanada, 2019; Jacobsen, 2002; Jacobsen & Wolsdorff, 2007; Kharkhurin, 2012; Spence & Deroy, 2013). This involves that participants have never been able to fully report their genuine experiences. This is of importance, as cross-modal correspondence is commonly defined as universal with low idiosyncrasy compared to synesthesia (Deroy & Spence, 2013). Greatly limiting the number of possible color responses may have led to shape-color associations to artificially appear more universally shared between individuals than synesthesia. Ward, Huckstep and colleagues (2006) investigated sound-color associations in synesthetes and non-synesthetes by offering both 48 pre-selected color chips and the possibility to precisely customize those colors. They found that synesthetes significantly used the color customizing option more often than non-synesthetes. Nevertheless, 61.6% of the non-synesthetes tested used the color customizing option, indicating that the need to report color associations with a high degree of precision is not rare for cross-modal associations. Having presented pitch-hue associations that do not match the ones commonly reported by individuals (Hamilton-Fletcher et al., 2017) may be a reason why Bernstein and colleagues (1971) failed to find congruency effects on a speeded classification task.

Shape-color correspondence has more recently been studied in the context of feature binding (Chen et al., 2023; Chen & Watanabe, 2020). Cross-modal correspondence have indeed been hypothesized as a potential factor involved in the binding problem (Spence, 2011), meaning how different features of a given stimuli that are processes by different brain areas get integrated together (Treisman, 1996). Shape-color correspondences appear as particularly important to understand, as they involve a pair of features that commonly co-occur in our environment (i.e., shapes and colors). Chen and colleagues (2020) found that incongruent shape-color associations significantly resulted in binding errors. Furthermore, this effect appears to be modulated by individual preferences in shape-color preferences (Chen et al., 2023). Congruent and incongruent feature conjunctions were, nevertheless, built based on the commonly reported associations at the group-level, in a one-to-one fashion (i.e., red-circle, yellow-triangle and blue square). Such paradigm choices can therefore produce more noisy and less reliable results, as their congruency conditions may not be optimally built at the individual-level. It is therefore important to better understand the patterns of shape-color associations in the general population and their degree of idiosyncrasy.

The study presented in Chapter 4 will therefore aim at investigating the variety of shape-color associations in the general Danish population, a population not tested before. A full color-wheel will be available for participants to reports there associations to five different geometrical shapes, allowing a more precise investigation of several aspects of color, namely the lightness, chromaticity, hue and color category aspects.

3.4.2. THE AUTOMATICITY OF THE SYNESTHETIC EXPERIENCE

Regarding synesthesia paradigms, past studies presented above claiming to have found a pop-out effect during visual search in synesthetes (Palmeri et al., 2002; Ramachandran & Hubbard, 2001a) were basing their conclusion on a premise that turned out to be untrue. That is, for the pop-out effect to occur, synesthesia needs to be pre-attentional. However, several studies presented above have shown that it is not the case (Ásgeirsson et al., 2015; Laeng et al., 2004; Rothen & Meier, 2009; Ward et al., 2010), meaning that pop-out effects previously found were likely false positives (Rothen & Meier, 2009). In light of those results, it is worth wondering whether the congruency effects found in the synesthesia Stroop truly tap into the synesthetic processes, or whether stimuli or task manipulations can also lead to false positives.

Dixon and colleagues (2004) proposed that associator and projector synesthetes showed opposite patterns of performances on two variations of the synesthesia Stroop due to differences in the automaticity of the their synesthetic experience. They further argued that in projector synesthetes, the processes leading to a synesthetic experience were more automatic than the ones leading to the perception of stimuli color. This account was made by applying MacLeod & Dunbar (1988)'s logic, by which the degree of automaticity of different processes can be ordered as a continuum based on the magnitude of the Stroop effect. There is nevertheless some discrepancy between Dixon and colleagues (2004) and MacLeod & Dunbar (1988)'s interpretations. MacLeod & Dunbar (1988) found that training an arbitrary color retrieval process in response to shape stimuli increased the amount of interference when participants had to name the color of the stimuli displayed and ignore the training. Reversely, the interference and facilitation that were present early in the training disappeared, showing that the more automatic the retrieval process, the more interference when having to name the color of the displayed stimuli. MacLeod & Dunbar (1988)'s study was performed in the context of the original Stroop effect and the implication of practicing a non-automatic process, to better understand whether the original Stroop effect was due to the reading process being faster or more automatized than the color naming one. The color retrieval process never got faster than the color naming one, therefore concluding that interference on the color naming task reflected a continuum of automaticity of the other process involved, namely the retrieval process. Contrary to Dixon and colleagues (2004), MacLeod & Dunbar (1988) did not made any assumption regarding the processes involved in the stimuli color perception. Instead, their interpretation was placed on the automaticity of the response to be made depending on the task, namely naming a physically presented color or retrieving a learned color.

Pritchatt (1968) had previously run a study investigating the effect on interference of training competing responses during retrieval. In a first group, participants learned to respond with a certain color name whenever they saw a certain non-sense syllable (i.e., training the color retrieval process). In a second group, participants learned instead to respond with a certain non-sense syllable whenever they saw a certain color patch (i.e., training the syllable retrieval process). Participants were then tested on two baseline conditions similar to the training (i.e., name the associated syllable when viewing a color patch and name the associated color name when viewing a syllable in black) and two conditions using syllables shown in a color incongruent to the training: consider only the color of the stimuli to retrieve the syllable associated to this color during training, and consider only the syllable to retrieve the color associated to this syllable during training. Participants showed an interference for the process they did not train (i.e., participants who trained the color retrieval process showed an interference in the syllable retrieval one, and participants who trained the syllable retrieval process showed an interference in the color retrieval one), showing like MacLeod and Dunbar (1988) that interferences in the retrieval task reflect a lack of automaticity compared to the other competing process involved.

Past studies have reported results that contradict the patterns found by Dixon and colleagues (2004) in associator and projector synesthetes (Hancock, 2006; Laeng et al., 2011; Levy et al., 2017; Mattingley et al., 2001; Mattingley & Rich, 2004; Nikolić et al., 2007). Nevertheless, no study to date has tried to evaluate whether an alternative hypothesis to the one stated by Dixon and colleagues (2004) was possible.

Two experiments are presented in Chapter 5 investigating three research questions. First, given the contracting results in past literature, do associator synesthetes really show larger congruency effects in the retrieval than color naming task, as claimed by Dixon and colleagues (2004)? Second, as congruency effects on the retrieval task was proposed to be due to a lack of automaticity of the retrieval process in participants trained for shape-color associations (MacLeod and Dunbar, 1988), does the retrieval synesthesia Stroop index synesthesia in the first place, and therefore can differentiate between associator synesthetes and non-synesthetes? Last, since congruency effects on the retrieval task can be increased by testing less trained processes (Pritchatt, 1968), does testing non-synesthetic associations increase congruency effects on the retrieval synesthesia Stroop in associator synesthetes?

3.4.3. CONFOUNDS THAT LEAD TO FALSE POSITIVE ON THE COLOR NAMING SYNESTHESIA STROOP

The color naming synesthesia Stroop has been found to produce congruency effects only in synesthetes, and not in non-synesthete controls (Dixon et al., 2000; Elias et al., 2003; Laeng et al., 2011; Mattingley et al., 2001; Mills et al., 1999; Nikolić et al., 2007; Odgaard et al., 1999). Several studies have therefore made use of the synesthesia Stroop in order to investigate whether non-synesthetes could be trained to acquire synesthesia (Bor et al., 2014; Colizoli et al., 2012; Elias et al., 2003; Kusnir & Thut, 2012; Meier & Rothen, 2009). The most extensive in-lab training was

performed by Bor and colleagues (2014) who trained non-synesthetes to associated 13 letters to colors, by practicing for 30 minutes, 5 days a week during 9 weeks. Post-training, participants showed a congruency effect in the color naming synesthesia Stroop, but only for letter-color associations that were previously found to co-occur commonly in both non-synesthetes and synesthetes (Rich et al., 2005; Simner et al., 2005). Critically, the congruency effect was also present before the training for those pairs, which the authors proposed was due to the intuitive aspects of those pairs.
Regan (1978) showed that the initial letter of color words were enough to cause a Stroop effect, by which the initial letter of the word primes the whole color word. Only three letters (i.e., R, G, B) were nevertheless tested.

The study presented in Chapter 6 aims at, first, replicating Regan (1978)'s results and extending them to more letter stimuli. Second, if Bor and colleagues (2014)'s interpretation is correct, and that such congruency effects are due to intuitive associations shared between both synesthetes and non-synesthetes (e.g., B is blue), synesthetes for whom initials of color words have synesthetic colors that differ from the intuitive ones (e.g., B is yellow) should not show a congruency effect when tested for intuitive associations. If on the other hand a congruency effect is found, it would indicate that full color word priming is stronger than the synesthetic experience, indicating that synesthesia Stroop paradigm run on both synesthetes and non-synesthetes attempted to be trained to acquire synesthesia should not include such letter stimuli.

CHAPTER 4. LOW IDIOSYNCRACY IN SHAPE-COLOR CORRESPONDENCES

4.1. INTRODUCTION

The universal aspects of cross-modal correspondence indicate that a given stimulus is associated to another stimulus from a different modality, and that little variability exists between individuals. However, no cross-modal correspondence seems to occur in 100% of the tested samples.
Ramachandran & Hubbard, (2001b) found that the name “kiki” was attributed to a spiky shape and the word “bouba” to a rounded shape in 95% of their tested sample, replicating previous results (Köhler, 1929). Their stimuli consisted of two shapes and two names shown at the same time and asking for a one-to-one pairing to be made. However, it seems that such a constrained paradigm may have overestimated the universality of the kiki-bouba effect. Indeed, when presented with both shapes and names simultaneously, 80% of the participants showed the expected effect, but when showed a single shape at a time and being allowed to choose either names for both shapes, the number of participants showing the kiki-bouba effect dropped to 60% (Nielsen & Rendall, 2011). It seems also that the pairing of the word bouba to the rounded shape is superior to the pairing of the word kiki to the spiky shape, and that presenting the bouba stimulus first can biase the effect (Cwiek et al., 2022). Furthermore, while most participants (71%) tested by Cwiek and colleagues (2022) found that the word kiki fits the spiky shape and bouba the rounded one, some felt the opposite way (11%) questioning the non-idiosyncratic aspect of the kiki-bouba effect, and the remaining ones associated both names to either the rounded shape (12%) or the spiky shape (6%), possibly showing a complete absence of this type of cross-modal correspondence in those individuals.

Yet, when only two shapes are presented with few response options offered, is it difficult to evaluate whether individuals who do not follow the expected cross-modal pattern are deprived of this type of cross-modal correspondence experience altogether or if they have their own idiosyncratic associations. This question can be explored by looking at a type of correspondence that occurs in a larger list of stimuli and where the reported answers are also allowed to greatly vary. As such, apart from made-up shapes showing a tendency to be given a certain name due to their visual features, the question of whether given geometric shapes have intrinsic colors attached to them has been around since before the phenomenon of cross-modal correspondence arose in cognitive science. Famous painter Kandinsky (1912) theorized that colors and shapes can be categorized as a function of their intrinsic warmth attribute. He proposed that the spikier the shape, the warmer it is. As a results the equilateral triangle’s acute angles fitted the warmth of the color yellow, the circle’s lack of angles fitted the cold color blue and the square's right angles fitted the medium warmth of red. He assumed that those associations were universal, and his survey run in 1922-1923 among members of the German art Bauhaus school, where he was a teacher, gave him reason. Almost a century later though, the claim was put to the test by scientists. All attempts to replicate Kandinsky's shape-color associations failed, whether they used a direct report method (Jacobsen, 2002; Jacobsen & Wolsdorff, 2007; Kharkhurin, 2012) or indirect methods (Kharkhurin, 2012; Makin & Wuerger, 2013). In fact, Kandinsky's proposed set of pairings was the least reported one among non-art students (Jacobsen, 2002), leading the author to hypothesize that Kandinsky's shape-color associations were rather idiosyncratic and due to synesthesia. But despite Kandinsky's proposed associations not been generalizable to the entire population and having issues replicating alternative associations, researchers continued to try to unveil tendencies in shape-color associations (see Table 4-1).

Italian (Albertazzi et al., 2013) and Japanese (Chen, Tanaka, Matsuyoshi, et al., 2015) participants were asked to report shape-color preferences for 12 different geometrical shapes (circle, square, triangle, parallelogram, rhombus, hexagon, trapezium, oval, pyramid, cone, truncated cone and truncated pyramid) from a set of 40 colors taken from the Natural Color System, at maximum chromaticity. While some common results appeared, major differences also occurred. Indeed, only 1/3 of the significant associations were found in both cultures (i.e., triangle-yellow, circle-red/yellow, pyramid-yellow, truncated pyramid-blue). The other associations were either present in Japanese but not in Italian participants (i.e., circle-orange, pyramid-blue, rhombus-yellow, trapezium-blue, truncated pyramid-yellow), present in Italian but not in Japanese participants (i.e., parallelogram-orange/blue/cyan, square-red/blue) or the color associations completely differed between countries (i.e., cone-blue in Italy but cone-yellow in Japan, hexagon-purple but hexagon-blue in Japan, oval-green in Italy but oval-yellow/orange/red in Japan). Similar to Kandinsky's claim though, shapes and colors' perceived warmth was proposed as a mediating factor for the significant associations (Chen, Tanaka, Matsuyoshi, et al., 2015).

Other hypotheses have also been put forward to explain significant shape-color associations (Fig. 4-1). Visual features of shapes have been hypothesized to influence the associations, such as line curvature and the presence of acute or square angles (Chen, Tanaka, Matsuyoshi, et al., 2015), or the precise angle degree values (Albertazzi et al., 2015). But some higher cognitive functions have also been hypothesized to be involved. Reference to everyday life items to make color choice has been put forward (Chen, Tanaka, Matsuyoshi, et al., 2015; Jacobsen, 2002; Kharkhurin, 2012) and emotion has also been hypothesized as a mediator of shape-color associations (Dreksler & Spence, 2019; Malfatti et al., 2014).

	Nationality	N	Circle	Triangle	Square
Kandinsky (1912)	Russian	1	Blue	Yellow	Red
Jacobsen (2002)	German	200	Yellow	Red	Blue
Jacobsen & Wolsdorff (2007)	German	74	Red	Yellow	Blue
Kharkhurin (2012)	United Arab Emirates	284	NA	NA	Blue
Albertazzi (2013)	Italian	60	Red/Yellow	Yellow	Red/Blue
Makin & Wuerger (2013)	British	36	NA	NA	NA
Chen,Tanaka, Matsuyoshi et al. (2015)	Japanese	138	Red/Yellow/ Orange	Yellow	Blue
Chen, Tanaka & Watanabe (2015)	Japanese	38	Red	Yellow	Blue
Chen, Tanaka, Namatame et al. (2016)	Japanese	91+95	Red	Yellow	Blue/Green
Dreksler and Spence (2019)	International	64	Red/Yellow	Red/Yellow	NA
Hanada (2019)	Japanese	50	Red	Yellow	NA
Chen et al. (2019)	Chinese	99+117	Red	Yellow	Blue
Chen et al. (2021)	Japanese	85	Red/Pink	Yellow	Blue

Table 4-1 Summary of findings from previous shape-color association studies, compared to Kandinsky's original proposal for the circle, triangle and square.
NA indicates no statistically significant associations found.

From a methodological point of view, the studies described above have not allowed participants to freely report their shape-color associations. A prime example of how forcing a one-to-one pairing can lead to a superficial alignment of reports, while relaxing constraints allows to observe a larger variety of tendencies is the kiki-bouba effect described above.

Similarly, in the context of shape-color associations, a one-to-one pairing has been forced (Jacobsen, 2002; Jacobsen & Wolsdorff, 2007), between the circle, triangle and square and yellow, red and blue. This resulted in an observed prevalence of circle-yellow, triangle-red, square-blue in 46% of the tested sample (Jacobsen, 2002), and circle-red, triangle-yellow and square-blue in 50% of the participants (Jacobsen & Wolsdorff, 2007). However, when allowing colors to be used independently for each shape, only the square-blue association was significant and present in 51% of the sample (Kharkhurin, 2012).

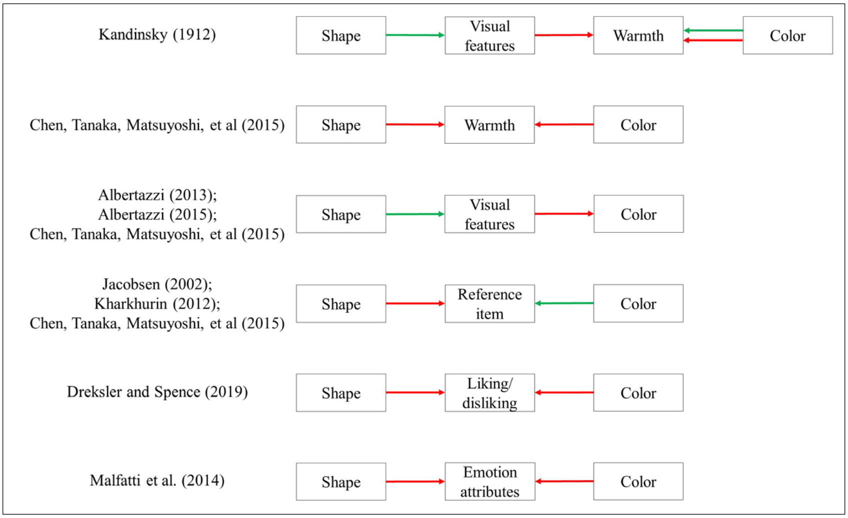

Figure 4-1 Summary of previous hypotheses proposed to explain shape-color associations. Arrows mark the direction of the influence on/from proposed mediating factors. Green arrows denote general principles, red arrows denote processes subject to individual variation.

Albertazzi et al. (2013) and Chen, Takana, Matsuyoshi et al. (2015) both offered 40 pre-selected color chips to report associations to the same 12 different shapes. Nevertheless, the chips selected were different, as Chen, Takana, Matsuyoshi et al. (2015) used for their direct report experiments the pre-selected chips that Albertazzi et al. (2013) used in a follow-up experiment aiming at evaluating the influence of stimuli size. Nonetheless, both sets of 40 pre-selected chips did not feature any pink, brown, white, black, gray or cyan for example, and for ease of analysis the color choices were collapsed into eight color categories (yellow, orange, red, purple, blue, blue-green, green, green-yellow). A first issue with this method is that, it does not take into account the 11 focal colors humans tend to categorize the color spectrum into (Berlin & Kay, 1969). Second, the pre-selected colors forming a gradient, the divide between categories is subjective. As a result, eight of the 40 chips selected by Albertazzi and colleagues (2013) ended up in a certain color category despite being barely perceptually different from a chip sorted in another category (International Organization for Standardization, 2013), potentially causing confusion in the data. Finally, forcing data into eight subjective color categories artificially inflates the count of reported colors for each of those categories, removing the variability that was originally present in the data, and therefore artificially inflating the non-idiosyncratic aspect of the associations reported.

The intra-modal aspect of grapheme-color synesthesia brings in the question of whether synesthesia should be strictly regarded as a union of the senses. It has indeed been proposed that grapheme-color synesthesia reflects an associations at the conceptual level of graphemes and colors (Chiou & Rich, 2014) rather than at the sensory one. The existence of shape-color association tendencies in the general population indicates that, like in synesthesia, the phenomenon does not strictly occur at the cross-modality level, but also between different dimensions of a same modality. As such, the conceptual level could be involved in shape-color associations in the general population, similarly to what has been proposed regarding grapheme-color synesthesia. Previous studies have indeed found that the first item of ordinal sequences that do not intrinsically entail color information (e.g., numbers, letters, weekdays) were significantly associated to the color red, in both synesthetes and non-synesthetes across cultures (Rich et al., 2005; Root et al., 2017; Rouw et al., 2014; Simner et al., 2005), indicating a conceptual associations between primacy and the color red. Furthermore, color associations correlated with the order of entry into language of color terms (Berlin & Kay, 1969) for such sequential items (Shanon, 1982; van Leeuwen et al., 2016), indicating that such items get paired to a color following the pattern in which colors categories emerge. The same pattern could therefore also be tested for shapes, as they also do not intrinsically entail color information and their number of sides can entail an ordinal organization.

In order to evaluate shape-color associations in a less restricted paradigm, the present study asked individuals to report intuitive color associations to a set of shapes using a full color space. Using a full color space allowed us to analyze color choices in terms of lightness, chromaticity, hue and color as a whole, and fully grasp the extend of variability in reported colors. Furthermore, the pattern of shape-color associations relative to the order of entry into language of color terms will be evaluated.

4.2. METHOD

4.2.1. PROCEDURE

The data collection was performed between September 2019 and August 2020 at the Trapholt Museum, Kolding, Denmark. The experiment was located in a quiet area of the museum, facing an undecorated white wall.

As being part of a museum exhibition, the data collection was subject to some constraints. As such the testing time had to be less than five minutes in total. Therefore, only five different shapes were tested, based on the estimation that color selection using a color wheel could take up to a minute to museum visitors less acquainted with touchscreen technologies.

The experiment begun with an instructions screen explaining the task ("*Pick the color that you feel fits each shape best, by pressing on the color wheel. When you are satisfied with the chosen color, press Next to see the next shape*"). The participants could decide whether the instructions would be displayed in Danish or English. A gif animation was also present to visually illustrate the task, using a star shape (not used as a stimulus during testing). A question mark-button could be pressed to access a step-by-step description of how to perform the task. The task would start when the participant would press the "Begin" button.

4.2.2. APPARATUS

Data was collected on a Windows 10 Lenovo Miix 320 10.1" two-in-one computer, consisting of an FHD screen with a 1920 × 1200 resolution and detachable keyboard, used in touchscreen mode. The experiment was run through a custom-made webpage in Chrome run in kiosk mode.

A wooden frame was used to secure the computer at a horizontal angle against the wall, 90 cm from the floor. The set-up did therefore not allow to control for viewing distance. For this reason, stimuli dimensions will be described in millimeter rather than visual angle degrees.

4.2.3. STIMULI

The stimuli consisted of five two-dimensional shapes (circle, triangle, square, pentagon, hexagon) presented against a gray background (RGB (219, 219, 219), 266 cd/m^2) one after the other. The dimension of each shape is shown in Fig. 4-2. At the beginning of each trial, a shape appeared on the right-hand side of the screen. The shape stimulus first appeared as a one-pixel black line with transparent filling. The full color-wheel (85 mm × 85 mm) was simultaneously displayed on the left-hand side of the screen, 33 mm away from the shape stimuli. The color wheel was rotated in a random fashion between each trial. A lightness bar (87 mm × 5 mm) was located just below the color-wheel. Upon touching a location on the color wheel, the corresponding color would automatically fill in the shape and the surrounding black line would disappear. Participants were allowed to change the color as many times as needed, until satisfied with the selected color. They would then need to press a “Next” button (33 mm × 12 mm) to move on to the next trial. The CIELab coordinates of only the last selected color were saved. In order to maintain engagement, a counter (20 mm × 10 mm) was displayed at the top right of the screen (See Fig. 4-3 for a screenshot of the experimental layout). Each shape was presented only once for each participant in a randomized manner, with no time constraints.

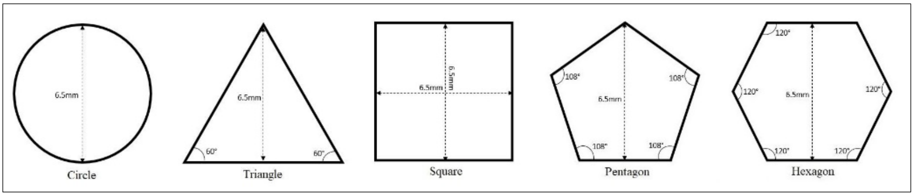

Figure 4-2 Dimensions of the shape stimuli.

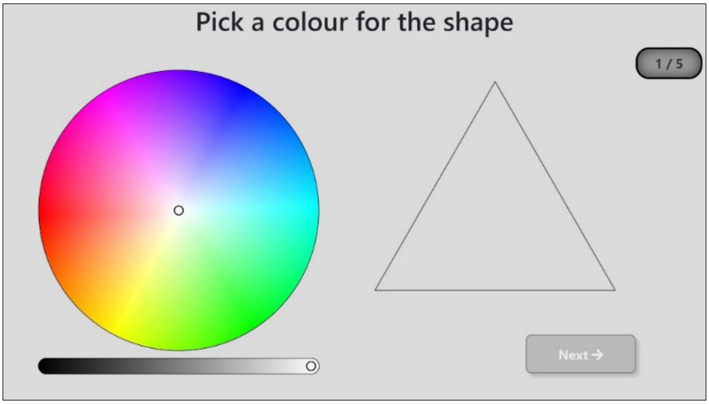

Figure 4-3 Screenshot of an experimental trial in English.

4.2.4. PARTICIPANTS

Out of the 8840 participants who completed the task, 106 were removed due to their data failing to be forwarded to the database. Colorblindness was reported by 196 participants and non-corrected abnormal visual acuity was reported by 195 further participants, who were therefore removed from the analysis. Data was carried on participants who reported being of Danish nationality (7549 participants) to control for potential cultural differences. Participants reporting an age below to six years-old and above 100 years-old were removed from the analysis due to potential typo when reporting age, and due to the possibility of parents performing the task for their young child.

A total of 7517 participants remained (5186 females; mean age = 37.1; SD = 19.7; range: 6-89 and 2331 males; mean age = 36; SD = 21.2; range: 6-100). A total of 993 participants reported having some type of synesthesia, nevertheless, since they had not been formally tested and did not indicate their specific type of synesthesia, we decided to include them in the analysis.

4.3. RESULTS

4.3.1. SHAPE-COLOR ASSOCIATIONS

A density-based spatial cluster analysis using the DBSCAN algorithm (Ester et al., 1996) was run, in order to detect areas of high-density of answers across all shape stimuli (epsilon parameter = 6; minPts parameter = 250). This resulted in eight clusters as shown in Fig. 4-4 in the CIELab color space and with CIELab values detailed in Table 4-2.

A chi-square test of independence was carried on the cluster count for each shape (5 × 8) and showed significant different associations of color for shapes (χ^2(28, N= 23755) = 3139.4, $p < 0.001$, ϕ_C= .18, $CI_{.95}$ [0.175, 0.187]).

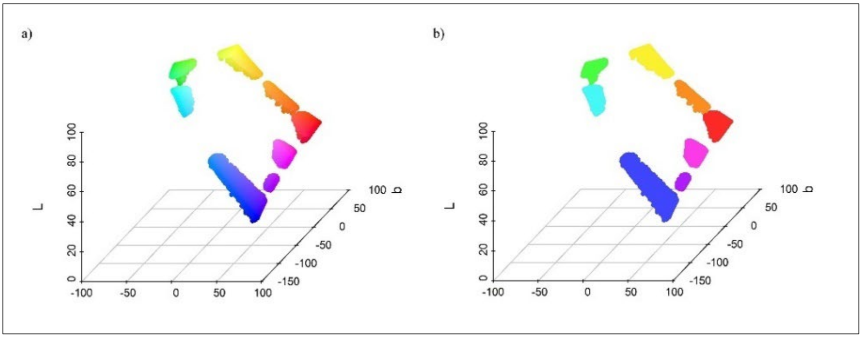

Figure 4-4 Position of the eight clusters of highly reported colors in the CIELab space. (a) The color of each point corresponds to its actual CIELab value. (b) The color of each point corresponds to the mean color of the cluster it belongs to.

Post-hoc residual analysis results (Bonferroni-corrected to the threshold $z > 3.23$ at $p < .05$) are shown in Fig. 4-5 and revealed that the circle was significantly more associated to colors located in clusters 3 and 5 (red and yellow), the triangle to colors in clusters 2 and 5 (green and yellow), the square to colors in cluster 1 (blue), the pentagon and hexagon to colors in clusters 4, 6, 7 and 8 (cyan, magenta, orange and purple).

Cluster	**L**	**a**	**b**	**Color name**	**Frequency**	○	△	□	⬠	⬡
1	42.09	57.96	-91.46	Blue	6132	798	841	2156	1168	1169
2	88.53	-77.97	72.75	Green	4135	498	1254	789	832	762
3	55	75.33	55.22	Red	4788	1609	909	975	648	647
4	89.65	-43.87	-11.45	Cyan	1552	230	284	256	381	401
5	93.23	-15.9	85.19	Yellow	3555	1188	1072	418	455	422
6	61.46	86.97	-46.92	Magenta	1954	296	334	239	514	571
7	70.03	36.07	70.11	Orange	1327	278	272	148	313	316
8	48.89	84.5	-79.89	Purple	312	33	36	29	121	93

Table 4-2 Mean CIELab values, color name and frequency count for the eight clusters resulting from the density-based cluster analysis.

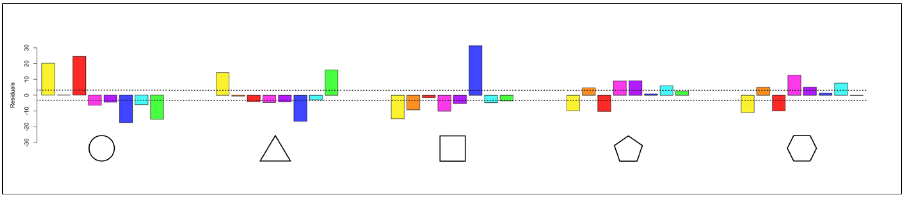

Figure 4-5 Chi-square residuals for each shape for each cluster ordered as a color gradient. The Bonferroni-corrected significance threshold is shown by the dash line. The colors displayed are the mean color for each cluster (CIELab value shown in Table 4-2).

4.3.2. SHAPE-HUE ASSOCIATIONS

The CIELab values have been converted using formula (1) to obtain the hue values of each trial for each participant in order to determine which specific hues are most associated to each shape.

$$H = tan^{-1}\frac{b}{a} \quad (1)$$

The obtained hue values were divided into 180 bins of 2° angles. Shape-hue associations were unveiled using a chi-square test of independence run on the count of answers (Fig. 4-6, left panel) for each bin and each shape (5 × 180). A significant association between hue bins and shapes was found ($\chi^2(716, N= 37259) = 4937.7$, $p < 0.001$, $\phi_C = .18$, $CI_{.95}$ [0.163, 0.174]) and a post-hoc residual analysis, Bonferroni-corrected to the threshold $z > 4.03$ at $p < .05$ (Fig. 4-6, right panel) was run to uncover specific significant shape-hue associations. The red and yellow hues significantly associated to the circle were located respectively at 50°-63° (peaking at 52°) and 340°-3°, plus 8° and 9° (peaking at 350°). The green and yellow hues significantly associated to the triangle were located respectively at 310°-317° (peaking at 314°) and 342°-359° (peaking at 346°). Regarding the square, the blue hues significantly more often chosen were located at 142°-162°, 166°, 167°, 170° and 171° (peaking at 144°). For the pentagon, significant hues were located in the purple regions at 128°, 129°, 132°-139° (peaking at both 128° and 136°). Finally, the hexagon was significantly more associated with orange, magenta and purple, respectively located at 22°-23° (both hue angles forming a peak), 114°, 115°, 118°-121° (peaking at 120°) and 124°, 125°, 128°, 129° and 130°-133° (peaking at 130°).

4.3.3. SHAPE-CHROMATICITY ASSOCIATIONS

Chromaticity values were retrieve using formula (2):

$$S = \sqrt{a^2 + b^2} \quad (2)$$

As presented in Section 3.1.2.3, every hue angle does not have the same possible maximum chromaticity. For this reason, an analysis run on the raw chromaticity values could be confounded by this aspect of color. Chromaticity values have therefore been normalized on a 0 to 100 scale, where 100 is the maximum chromaticity value possible for each given hue angle.

A one-way repeated measures ANOVA was run on the normalized chromaticity, as a function of Shape, where a significant main effect was found $F(1, 3.85) = 21.58$, $p < .001$, $\eta_p^2 = .002$. Post-hoc Bonferroni-corrected paired-sample t-tests revealed that the triangle was associated to higher chromaticity ($M_T = 85.2$) than all four other shapes ($M_C = 83.5$; $M_S = 83.7$; $M_P = 83.3$; $M_H = 83.1$), all $p < .001$. All other shapes did not significantly differ in their chromaticity values.

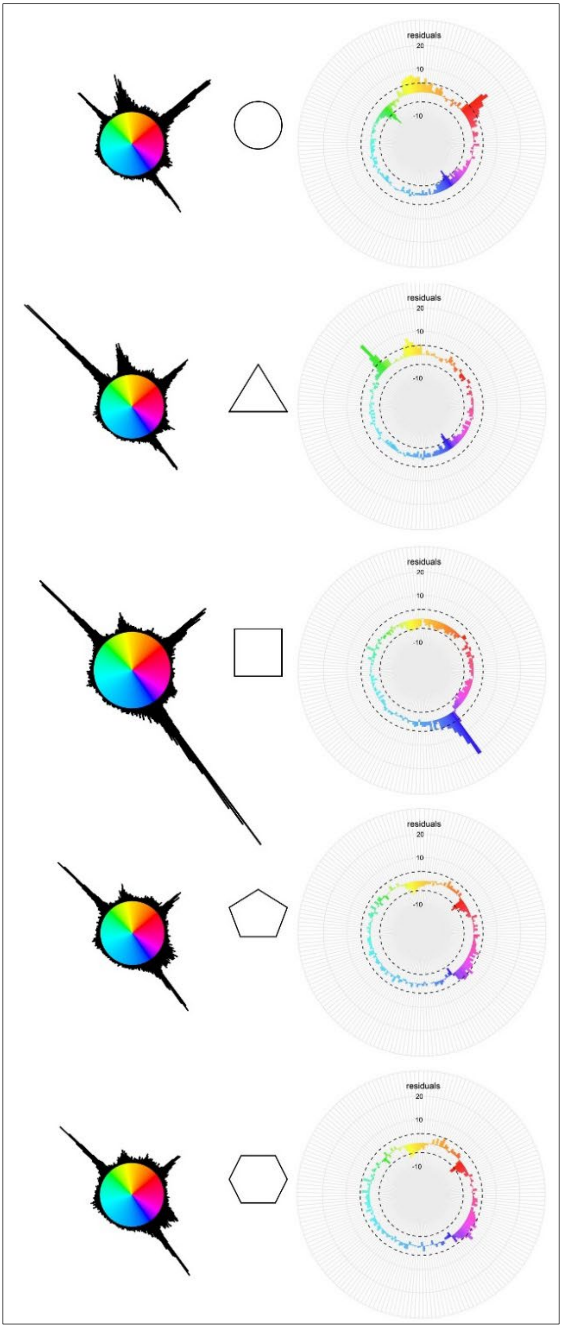

Figure 4-6 Count of responses for each shape and each hue bin, and corresponding chi-square residuals.
The color of each bin is represented at maximum chromaticity. The dash line in the circular bar plot on the right represents the Bonferroni-corrected significance threshold.

4.3.4. SHAPE-LIGHTNESS ASSOCIATIONS

A one-way repeated measures ANOVA was run on the lightness value of color responses as a function of Shape. A significant main effect was found F(3.94, 29633.17) = 281.03, $p < .001$, $\eta_p^2 = .029$. Post-hoc Bonferroni-corrected paired-sample t-tests showed that all shapes were significantly different from each other regarding associated lightness, except for the pentagon and hexagon. The darkest shape was the square ($M_S = 61.2$), followed by the hexagon and pentagon ($M_P = 66.5$; $M_H = 66.4$), the circle ($M_C = 69.2$), and finally the triangle featured the lightest colors ($M_T = 71.7$), with all significant $p < .001$.

4.3.5. INTERACTION BETWEEN SHAPE-HUE ASSOCIATIONS AND CHROMATICITY

Each answer for each participant has been classified as either in line with the significant shape-hue associations found above or not, in order to find out whether the chromaticity values of shape-hue associations commonly chosen at the group level differ from rarer ones. Out of the total 7517 participants, 2947 chose the hue significantly chosen at the group-level for the circle, 2351 for the triangle, 2294 for the square, 408 for the pentagon and 747 for the hexagon. The remaining participants chose instead a hue that was not significantly chosen at the group-level (i.e., circle: 4570, triangle: 5166, square: 5223, pentagon: 7109, hexagon: 6770). A two-by-two ANOVA was run on the normalized chromaticity as a function of Shape (5 levels) and Significance (2 levels). A main effect of Significance, F(1, 37575) = 482.64, $p < .001$, $\eta_p^2 = .013$, revealed that significant shape-hue associations have a higher chromaticity value than non-significant ones (significant associations: M = 87.6; non-significant associations: M = 82.6).

A significant interaction of Significance and Shape was also found, F(4, 37575) = 38.63, $p < .001$, $\eta_p^2 = .004$. Post-hoc Bonferroni-corrected pairwise comparison showed that the effect was present for the circle, triangle and square (all $p < .001$), but not for the pentagon and hexagon (Fig. 4-7-left). Furthermore, for the significant shape-hue associations, two groups of shapes appeared, with on one side the circle (M = 88.4), triangle (88.2) and square (M=88.5) which had chromaticity values that significantly differed from the ones of the pentagon (M = 82.1) and hexagon (M = 83.2) (all $p < .05$).

4.3.6. INTERACTION BETWEEN SHAPE-HUE ASSOCIATIONS AND LIGHTNESS

A similar analysis was run regarding interaction between shape-hue associations and lightness values. A two-by-two ANOVA run on the lightness value as a function of Shape and Significance showed a main effect of Significance F(1, 37575) = 103.98, $p < .001$, $\eta_p^2 = .003$, whereby non-significant shape-hue associations were brighter than significant ones (significant associations: M = 65.7; non-significant associations: M

= 67.4). A significant interaction of Significance and Shape was found, F(4, 37575) = 1710.38, $p < .001$, $\eta_p^2 = .154$. Post-hoc Bonferroni-corrected pairwise comparison showed that while the circle and triangle are brighter in their significant hues than in the non-significant ones, the opposite occurs for the square, the pentagon and hexagon, being less bright in their significant hues than in the non-significant ones, with all $p < .001$ (Fig. 4-7-right).

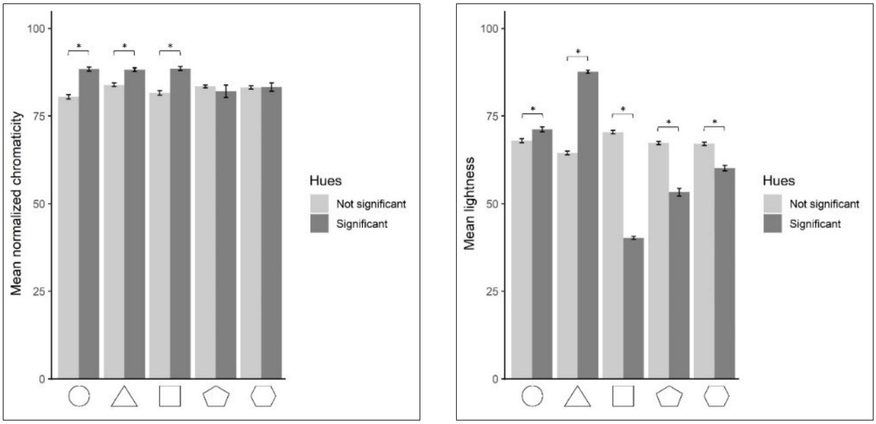

Figure 4-7 Mean normalized chromaticity (left) and lightness (right) for each shape, for hues significantly and non-significant associated to each shape.
The error bars depict 95% confidence intervals and asterisks mark the statistically significant comparisons at $p < .05$.

4.3.7. CORRELATION WITH ORDER OF ENTRY INTO LANGUAGE OF COLOR TERMS

In order to investigate whether shape-color associations are correlated with the order of entry into language of color terms (Berlin & Kay, 1969), each data point was converted into a Berlin-Kay color category, using the Colournamer tool (Mylonas et al., 2013). The shapes have also been ordered from least to most complex, as denoted by their number of sides (i.e., ordered as: circle, triangle, square, pentagon, hexagon). A Spearman's Rho correlation analysis revealed a small but significant correlation between entry into language order and shape complexity ($\rho = .17$, $p < .001$), indicating a tendency for shape complexity order to be mapped onto color name entry into language order.

Ease of color name generation order and color name frequency order could also be involved in shape-color associations. A Spearman's Rho correlation analysis was run on the shape complexity order as a function of ease of generating color names (Battig & Montague, 1969) and color word frequency in Danish (based on the DaTenTen20 corpus). No correlation was found for the ease of generation order ($\rho = .006$, $p = .175$), but a small significant correlation appeared for color name frequency order ($\rho = .057$, $p < .001$). However, color word frequency appears to highly correlate with entry into language order (ρ = .753, p < .001), suggesting that the small correlation between color name frequency and shape complexity could be due to the fact that it also closely follows the entry into language order.

Fig. 4-8 shows the correlation between the ease of generation (a), color name frequency (b), and entry into language (c) orders and shape complexity.

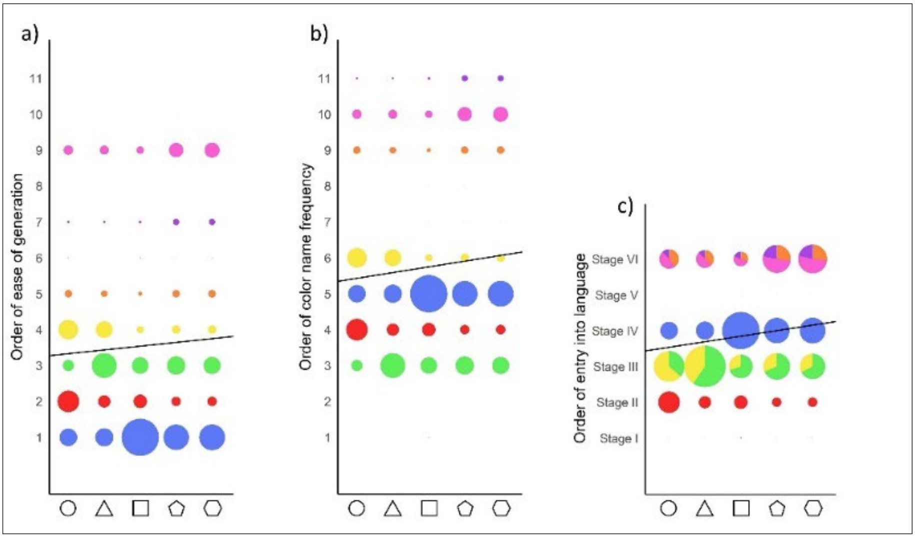

Figure 4-8 Correlation between the ease of generation (a), color name frequency (b), and entry into language (c) orders and shape complexity.
Dot sizes denote the frequency of response, and the solid black line represents the correlation line. The color of each color is the average color chosen for each color category. For entry into language stages that contain several color categories (c), the proportion of responses for each color category is represented on the dots.

4.4. DISCUSSION

Different color associations have been found for the circle, triangle, square, pentagon and hexagon in the Danish population. Namely, the circle was associated to red, spanning over most of the spectrum of red hues and to yellow, nearly spilling over the neighboring green and orange hues, and with high chromaticity and medium lightness values. The red color cluster contained more responses for the circle than the yellow one (respectively chosen by 21% and 16% of the participants). The triangle was mainly associated to green, covering a small range of possible green hues, and to yellow, here covering a more restricted spectrum of yellow answers than for the circle, and with both high chromaticity and lightness values. The green and yellow color clusters were chosen by rather equal proportions of the sample (respectively 17% and 14%). Regarding the square, only blue came out as significantly more often chosen, covering here a very restricted range of blue hues, which have a high chromaticity and very low lightness values. Despite the blue colors chosen being a very specific portion of the full blue spectrum, it was the shape-color association the most largely shared among participants (29%). The pentagon was more often associated to cyan, purple, and magenta compared to other shapes. However, only the purple hue spectrum showed specific peak hues, one bordering the magenta area and another one in the purple region. Those significant hues were associated with medium-low lightness, but their chromaticity values did not differ from less often chosen hues, marking a pattern differing from the circle, triangle and square. The cyan, purple, magenta, and orange despite being significantly more often chosen for the pentagon than average, were still quite marginal choices (respectively chosen by 5%, 2% 7% and 4% of the participants). The color choices for the hexagon resemble a lot those of the pentagon, being significantly more often associated to cyan, purple, magenta, and orange, and with medium lightness, and chromaticity values that did not differ from the less often chosen hues. The orange hues significantly chosen were very specific whereas a larger variety of purple and magenta hues were chosen. Oppositely, no specific cyan hue stood out. Here again the significant cyan, purple, magenta, and orange color choices, despite being higher than average, where quite marginal (respectively chosen by 5%, 1%, 8% and 4% of the participants).

4.4.1. PARTICIPANTS' FREE REPORTS COMPARED TO PRE-SELECTED COLOR CHIPS

A key motivation for this study was to evaluate whether past shape-color studies, that used pre-selected color chips, managed to offer a range of colors close to those that individuals would freely select. As gathered in Table 4-3, the pre-selected color chips from studies that used the Natural Color System (Albertazzi et al., 2013; Chen, Tanaka, Matsuyoshi, et al., 2015; Malfatti et al., 2014) differed quite largely from colors instinctively picked by participants when allowed to freely navigate a full color space. Particularly, the cyan color was not available at all and the alternatives to the magenta and purple colors were very dissimilar in the study by Albertazzi and colleagues (2013). The colors offered were slightly closer to our results in the study by Chen, Tanaka, Matsuyoshi and colleagues (2015). Nevertheless, overall, the pre-selected color chips were far more muted (smaller values on the *a* and *b* CIELab axes) than the colors freely selected by participants. This is of importance as our sample of participants had a tendency to select colors with a higher chromaticity value for significant color associations to the circle, triangle and square. Many past shape-color studies have chosen to control their pre-selected color chips for chromaticity (Albertazzi et al., 2013; Chen, Tanaka, Matsuyoshi, et al., 2015; Dreksler & Spence, 2019), hiding the fact that significant shape-color associations also come with higher chromaticity for the circle, triangle and square. Colors with higher chromaticity values tend to cause higher arousal levels (Wilms & Oberfeld, 2018) and tend to be preferred to colors of low and medium chromaticity (Palmer & Schloss, 2010). Interestingly, chromaticity differences between significant and non-significant shape-hue associations were only observed for the circle, triangle and square, which also showed more largely shared associations across the tested sample. The pentagon and hexagon on the other hand had significant shape-color associations that were shared among fewer individuals, and the preferred hues did not show higher chromaticity values than all other hues. The strength of the association at the group level seems therefore reflected in higher chromaticity values.

Cluster	Color name	Albertazzi et al. (2013)	Cluster color	Chen, Tanaka, Matsuyoshi et al. (2015)
1	Blue	15.36	🟦	11.02
2	Green	22.35	🟩	11.75
3	Red	11.55	🟥	9.23
4	Cyan	24.50	🟦	20.70
5	Yellow	9.58	🟨	6.27
6	Magenta	21.51	🟪	15.82
7	Orange	7.27	🟧	3.49
8	Purple	23.63	🟪	14.66

Table 4-3 Closest color chip used by Albertazzi et al. (2013) and Chen, Tanaka, Matsuyoshi et al. (2015) compared to the mean color of the color clusters reported by participants in the present study.
Number in the cells are the perceptual difference values (DeltaE, International Organization for Standardization, 2013) between the mean color of each cluster and the closest color chip used by Albertazzi et al. (2013) and Chen, Tanaka, Matsuyoshi et al. (2015).

4.4.2. LESSONS FROM REPORTS OF SHAPE-COLOR ASSOCIATIONS USING A FULL COLOR SPACE

Danish participants significantly associated the circle to red and yellow, the triangle to green and yellow, the square to blue and the pentagon and hexagon to magenta, purple, cyan, and orange.

First of all, those associations are not extremely different from those reported in past studies (Table 4-1). Specific differences though occurred, especially regarding the strong association between the triangle and green, which has surprisingly never been attested before. This could be due to cultural differences in the Danish population. Nevertheless, the particular types of green selected by the Danish participants were not available in past studies using pre-selected color chips. It is therefore a possibility that, when deprived from the option of selecting the correct type of green (with high chromaticity and lightness), participants decided to select instead the yellow chip, which is the second most common choice in Danish participants at the group level, and which featured also rather high chromaticity and lightness values in the pre-selected chips from previous studies (Table 4-1).

Second, each shape was not associated to one or several colors with the same degree of agreement between participants. The square-blue association was the most widely shared (29% of participants) and the types of blue selected were highly specific. The triangle was associated with a small range of green and yellow with more agreement (respectively 17% and 14%) than for red and yellow hues for the circle, where the circle-red association was more common (21% of participants) than the circle-yellow one (16% of participants), with a range of chosen colors spanning over the whole red and yellow hue spectrums. Oppositely, the pentagon and hexagon had significant color associations to magenta, purple, cyan, and orange that were shared by only few individuals (1% to 8% of the participants), and with few specific hues standing out. Third, while the square was significantly associated to only one color, the four other shapes were associated to several colors. This questions the degree to which shape-color correspondences could be idiosyncratic. There is no reason to think that participants who associated the triangle to green are subjected to cross-modal correspondence to a higher or lesser degree than those who associated the triangle to yellow. The driver for triangle-color associations could be a core triangle-high lightness association, which then results in personal preferences for choosing either yellow or green. Nevertheless, finding a core rational does not erase the fact that the final color choice goes towards two major directions (yellow or green). Similarly, for the circle, the rational for red and yellow associations may be a tendency to refer to an environmental object as previously argued (Chen, Tanaka, Matsuyoshi, et al., 2015; Jacobsen, 2002; Kharkhurin, 2012), or mediation through perceived warmth (Chen, Tanaka, Matsuyoshi, et al., 2015), or also emotional judgement (Dreksler & Spence, 2019), but in the long run, a group of individuals will land on the color red, while others on the color yellow. As such, shape-color associations, as well as other types of cross-modal correspondence possibly, may not be as non-idiosyncratic as previously argued.

4.4.3. REEVALUATING THE LOW IDIOSYNCRATIC ASPECT OF CROSS-MODAL CORRESPONDENCES

Synesthetic associations have long been defined as idiosyncratic (Deroy & Spence, 2013; Grossenbacher & Lovelace, 2001). Meaning that if for a certain person "A" is yellow, but for another one is it blue, it is because, by nature, each synesthete has their own arbitrary associations, and neither synesthete is more correct than the other. Nevertheless, literature has shown that underlying patterns of associations exist for synesthesia. For example, the first item of a list is commonly associated to red (Itoh & Nakada, 2018; Root et al., 2017; Rouw et al., 2014), semantic grapheme-color associations often occur (Mankin & Simner, 2017; Rich et al., 2005; Simner et al., 2005), stereotypes can influence associations (Root et al., 2019) and childhood toys may be at the source of shared grapheme-color associations in up to 15% of synesthetes (Witthoft et al., 2015; Witthoft & Winawer, 2006). At the same time, in cross-modal correspondence, the kiki-bouba effect that was thought to occur in 95% of the population (Ramachandran & Hubbard, 2001b) seems to have be greatly overestimated and could occur in as low as 60% of the population when controlling for possible methodological confounds (Nielsen & Rendall, 2011, 2013). As such, it seems quite possible that cross-modal correspondence can show degrees of idiosyncrasy that match those of synesthesia, with several patterns of associations co-exist in the population (e.g., triangle-green and triangle-yellow), and some individuals show patterns opposite to the majority of the population (e.g., triangle-red or triangle-blue). In an early study on loudness-lightness correspondence, were pitch loudness was found to positively correlate with lightness values (Marks, 1974), it was indeed already mentioned that two out of 12 participants followed an opposite pattern, were pitch loudness negatively correlated with lightness values.

Direct reports of cross-modal associations, which are unconscious, lead to great variability in the data, as participants are reporting intuitive answers, rather than their perceptual ones, as in synesthesia. Pitch-color cross-modal correspondence showed indeed low consistency compared to synesthetes' report of color experiences for pitches, even after as little as a 10 minute-interval (Ward, Huckstep, et al., 2006). Establishing the existence of a certain type of cross-modal association using direct report methods implies detecting a certain pattern in the population. Such a pattern can be better found if variability between participant is low, especially with small samples of participants. Once the existence of a certain cross-modal correspondence has been unveiled, a larger number of participants allows, however, to evaluate the variety of experiences. In the case of shape-color correspondences, this means more precise information regarding both the color categories selected for a given shape, as well as the variability within color categories. Although the degree of idiosyncrasy in cross-modal correspondence has been formulated (Spence, 2011), it is not yet known the extent to which cross-modal correspondences vary between individuals, and whether the degree of idiosyncrasy is similar for all types of cross-modal correspondence.

The present study reports patterns of association that co-exist in the general population (e.g., circle-red and circle-yellow; triangle-yellow and triangle-green). This is of importance as a single pair of shape-color associations are usually tested across all participants in paradigms based on congruency of associations at the group-level (Chen et al., 2023; Chen, Tanaka, Namatame, et al., 2016; Chen & Watanabe, 2020; Makin & Wuerger, 2013). Future paradigms may therefore need to customize their stimuli list to fit individuals' preferences, similar to practices in synesthesia research.

Finally, only shape-color associations have been tested here. The same paradigm could be run on other types of associations to evaluate whether similar a tendency for co-existing associations can be generalized. Furthermore, shape-color associations are a case of intra-modal associations. It would therefore be interesting to also study associations across modalities, in order to evaluate whether associations at the modality and dimension level show differences regarding their degree of idiosyncrasy.

4.4.4. THE INVOLVEMENT OF PROTOTIPICALITY IN SHAPE-COLOR CORRESPONDENCES

In his original claim, Kandinsky considered only three shapes (circle, equilateral triangle and square) which happen to be the three prototypical shape categories, according to the Gestalt psychology of "good form" (Rosch, 1973). Similarly, the red, blue and yellow he proposed are members of the four psychological primary color categories (red, blue, green, and yellow; Abramov & Gordon, 1994; Kay & McDaniel, 1978; Valberg, 2001; Witzel & Franklin, 2014). In our study, despite showing a variety of associations for almost every shape, participants tended to associate the three prototypical shapes (circle, equilateral triangle and square) to one or many of the psychological primary color categories (red, blue, green, and yellow), while the pentagon and hexagon, which are not prototypical shapes, where significantly associated to secondary colors (orange, purple, magenta, cyan). This could indicate that shape-color associations occur at the conceptual level of shapes and colors identities. Furthermore, as previously found for graphemes and weekdays (Shanon, 1982; van Leeuwen et al., 2016), shape ordinality, as denoted by shape complexity, showed a small correlation with the order of entry into language of color terms (Berlin & Kay, 1969). Previous authors had not ventured any interpretation as to why this pattern occurred, however.

The pattern of acquisition of color terms was first argued to follow the entry into language (i.e., white/black, red, yellow/green, blue, brown, purple/pink/orange/gray) presented by Berlin and Kay (1969). When testing 669 pre-school children aged 30 to 53 month-old (Johnson, 1977), the pattern of acquisition of color terms (red, green, black, white, orange, yellow, blue, pink, brown, purple) followed to some degree the order described by Berlin and Kay (1969). However, it has been claimed instead that children acquire all the color terms between 35.6 and 39.5 month-old, except for the terms brown and gray that are acquired only 9 months later (Pitchford & Mullen, 2002, 2005). However, regardless of the precise order of acquisition of color terms, a recurring pattern can be observed where the term red is the first term acquired (Kay & Maffi, 1999).

The acquisition of color terms in children, between 20 and 39 month-old, appears to be dependent on their capacity to form a representation of colors at an abstract level, however, the knowledge of a single color term seems enough to obtain color abstraction (Kowalski & Zimiles, 2006), and the lateralization of color categorization switches from right to left hemisphere as color terms are acquired (Franklin et al., 2008). While color term acquisition seems to be completed around 3 to 4 years-old, this is not the case for shape acquisition. The circle is the most easily identifiable shape in 3-4 year-old children, the square is also commonly identified but takes longer to be fully mastered, while the triangle is still not acquired by 6 years-old (Aslan & Arnas, 2007; Clements et al., 1999, 2018; Clements & Sarama, 2000; Yin, 2003). If shapes get paired to a color as they get learned, since primary and secondary colors appeared to be acquired at the same time in children (Pitchford & Mullen, 2002, 2005), it does not explain why the circle, triangle and square are all associated to primary colors (i.e., red, blue, green, and yellow) only and the pentagon and hexagon to secondary colors (orange, purple, magenta, cyan). Instead, a first sorting seems to occur based on prototypicality (i.e., prototypical shapes mapped into prototypical colors and non-prototypical shapes mapped into non-prototypical colors). Nevertheless, in our results, the primary colors are not equally associated to each of the prototypical shapes, and in fact, the colors blue and green were significantly less chosen for the circle, the color blue was significantly less chosen for the triangle and the color yellow was significantly less chosen for the square (Fig. 4-5). Namely, while the blue cluster was the most chosen across shapes (Table 4-1), it was though chosen nearly three times less (798 times) for the circle compared to for the square (2156 times). It seems therefore that a first sorting based on prototypicality occurs, and then in a second step, each shape gets attributed a specific color, possibly with a bias towards following the progression of entry into language of color words.

If cross-modal correspondence is to show levels of idiosyncrasy similar to those of synesthesia, a remaining key difference with synesthesia is its unconscious aspect. Indeed, while synesthetes report physically experiencing their concurrent, it is not the case for cross-modal correspondence.

CHAPTER 5. THE MECHANISMS INVOLVED IN THE SYNESTHESIA STROOP

5.1. INTRODUCTION

Due to the automatic aspect of synesthesia, grapheme-color synesthetes have been found to demonstrate a congruency effect in a modified Stroop task (Dixon et al., 2000). In the synesthesia Stroop, the congruency condition is built relative to the grapheme-color associations of the individual, who are asked to name the color of the stimuli displayed, ignoring their synesthetic color. Response times are then slower in the incongruent condition than in the neutral and congruent conditions, demonstrating that the presence of a synesthetic color interferes with the color naming process (Dixon et al., 2000). A few years later, the paradigm got extended in order to test whether associator and projector grapheme-color synesthetes, who perceive the concurrent colors respectively in their mind's eye and projected externally, show the same interference depending on the location of their experience (Dixon et al., 2004; Ward et al., 2007). To do so, two different tasks were used. Participants were presented with digits (Dixon et al., 2004), or digits and letters (Ward et al., 2007), in colors incongruent or congruent to their synesthesia. In a first task, they were asked to name the color of the stimuli displayed, ignoring their synesthetic experience, while in a reversed task, synesthetes had to retrieve their synesthetic experience, ignoring the color of the stimuli displayed. The former task is commonly called an "ink-naming task" and the latter a "retrieval task". No controls were used, and the lack of a baseline condition made it impossible to conclude whether differences in response times between congruency conditions were due to an interference in the incongruent condition or facilitation in the congruent one. Congruency effects were therefore used instead, calculated as the difference in mean response time in the incongruent and congruent conditions. Dixon and colleagues (2004) found that associators had a larger congruency effect and slower response times in the retrieval task, while for projectors the congruency effect was larger and response times slower in the ink-naming task. The authors hypothesized that the differences between associator and projector synesthetes would be due to external color experiences being harder to ignore, due to those being more intense than the internal ones, as well as due to the close location of the synesthetic color and stimuli color in projectors. MacLeod and Dunbar (1988) proposed that differences in the magnitude of the congruency effect on the ink-naming and retrieval task of the Stroop paradigm reflect a continuum of automaticity of the processes involved. Following this proposal, Dixon and colleagues (2004) concluded that differences in automaticity may also be at play, where in projector synesthetes the processes causing the synesthetic color experience are more automatic than in associator synesthetes, and that in projector synesthetes these processes are more automatic than the processes leading to the perception of the stimuli color. The synesthesia variation of the Stroop task was therefore argued to be able to assess the automaticity of the synesthetic experience, as well as being able to differentiate between subgroups of synesthesia, at the group level (Dixon et al., 2004).

While Dixon and colleagues (2004) placed their interpretation of the continuum of automaticity at the level of the synesthetic processes, MacLeod and Dunbar (1988) proposed that it is the ink-naming and the retrieval processes themselves that represent a continuum of automaticity. Also, contrary to Dixon and colleagues (2004) who proposed that larger congruency effects in the ink-naming then retrieval task in projectors were due to the processes leading to the synesthetic experience being more automatized than those leading to the perception of the stimuli color, MacLeod and Dunbar (1988)'s account did not make assumption about the automaticity of the stimuli color perception. Indeed, although the purpose of the study was completely unrelated to synesthesia, MacLeod and Dunbar (1988) featured a paradigm similar to the one used by Dixon and colleagues (2004), investigating the automaticity of the ink-naming and retrieval processes in the general population. Here, they conducted three experiments that consisted in a shape-color training phase where participants had to name a previously defined color (green, pink, orange, or blue) upon seeing a given non-geometrical shape (similar to a Stroop retrieval task, with all stimuli presented in white). Importantly, during training, the participants were informed of the shape-color associations only by reading the color name to be associated to each shape, and never saw the actual color on the shape. As such, the trained color associations were verbal information, not perceptual color ones. This training phase lasted for two hours in the first experiments, for five hours in the second experiment and for 20 hours in the last experiment. Trained participants then took an ink-naming task and a retrieval task (called "shape-naming" in the original study). Stimuli were displayed in colors either incongruent or congruent to the training, or black as baseline. After two hours of training, both an interference and facilitation were present in the retrieval task, but not in the ink-naming task. After five hours of training, both the interference and facilitation remained in the retrieval task and an interference appeared in the ink-naming task, and the effect persisted for at least three months post-training. Finally, after 20 hours of training, both the interference and facilitation disappeared from the retrieval task and the interference increased in the ink-naming task. The authors proposed that this reversal in interference pattern was due to an inversion in automaticity. By nature, the ink-naming process is more automatic than the color retrieval process, which is demonstrated by both the interference and facilitation that the color information had on the retrieval task, coupled with faster RTs in the ink-naming task than retrieval task with a short training. After five hours of training, both processes reached the same level of automaticity, they therefore both managed to interfere with each other. After 20 hours of training, the retrieval was now more automatic than the ink-naming process, causing the automatically retrieved information to interfere with the color-naming process.

It can be noted that since synesthesia was not the focus of the study, participants have not been asked whether they experienced synesthesia-like color sensations after training.

Based on MacLeod and Dunbar (1988)'s proposal, the results from Dixon and colleagues (2004) could also be interpreted as differences in the automaticity of the ink-naming and retrieval processes themselves, rather than a reflection of differences in automaticity of the synesthetic experience, or differences in automaticity of the processes involved in synesthetic and stimuli color perception in projectors. As such, for projector synesthetes, the larger congruency effect in the ink-naming task could reflect a more automatized retrieval than ink-naming process, and in associator synesthetes, the larger congruency effect in the retrieval task could reflect a more automatized ink-naming than retrieval process, while for both subgroups the synesthetic experience is equally automatic.

Rothen, Tsakanikos, and colleagues (2013) found that the magnitude of the congruency effect on the retrieval task was negatively correlated with the reported amount of effort (degree of automaticity) needed for the color experience to occur. In other words, the more automatic the synesthetic experience, the less interference in the retrieval task. Inversely however, no correlation was found between the magnitude of interference in the ink-naming task and reported degree of automaticity. Those results show that the degree of automaticity of the synesthetic experience does not form a continuum that is reflected in the ink-naming task of the synesthesia Stroop. As such, Dixon and colleagues (2004)'s proposal that larger congruency effects in the ink-naming task in the projector group is due to more automatized synesthetic experiences does not seem to hold.

Studies that have since then used the synesthesia Stoop have obtained results that also did not follow the expected dichotomous associator-projector performances. Hancock (2006) tested monozygotic twins who reported internal concurrent colors to graphemes, but who were still subject to a congruency effect in the ink-naming task. Similarly, in a projector synesthete, the retrieval task caused a larger congruency effect than the ink-naming one (Laeng et al., 2011). Few have though expressed doubts regarding Dixon and colleagues (2004)'s claim, as the main purpose of later studies was not to confirm the validity of dichotomous performances, but to estimate whether their synesthete participants were projectors or associators. Only Mattingley and Rich (2004) pointed out that the 15 associators they had previously tested (Mattingley et al., 2001) showed, as a group, a congruency effect on the ink-naming task, contrary to Dixon and colleagues (2004)'s claim. Furthermore, the effect was present at the individual level in all but three of the associator participants tested by Mattingley and Rich (2004). Dixon and colleagues (2004) therefore clarified that while only *some* associators may show congruency effects in the ink-naming task, *all* projectors would do so. Importantly though, congruency effects on the synesthesia Stroop are commonly not statistically tested at the individual level, therefore conclusions were based on average response times in the incongruent condition being simply mathematically superior to the ones in the congruent condition. Ward and colleagues (2007) repeated Dixon and colleagues (2004)'s paradigm and confirmed their conclusions. However, they did not find any significant interaction of task (ink-naming vs. retrieval), congruency condition (congruent vs. incongruent), and group (associators vs. projectors). Their results only showed that associators were significantly faster on the ink-naming task across congruency conditions while projectors were faster on the retrieval task. All five projectors tested by Dixon and colleagues (2004) followed this pattern, here again based on mathematical observations, and five out of seven associators did so, possibly showing that, similarly to congruency effects, the response time pattern is more stable in projectors than associators. Nonetheless, Ward and colleagues (2007) indicated that in their replication, the effect was present in five out of seven projectors and six out of seven associators. Importantly though, two synesthetes who had reported external color experienced were sorted out into the associator group, and had indeed performances matching associator patterns (Ward et al., 2007), challenging the idea that self-reported external experiences lead to invariable projector-like performances (Dixon et al., 2004).

Even more importantly, the opposite performances of associators and projectors at the group level may have been overestimated from the very beginning, as conclusions were in fact based on results above the statistical threshold, which prompted the authors to conclude for *marginal* effects (Dixon et al., 2004). Both Ward and colleagues (2007) and Dixon and colleagues (2004)'s studies were underpowered, particularly regarding the associator group (Faul et al., 2009). For these reasons, the performance of associator synesthetes in the synesthesia Stroop remains unclear regarding the extent to which it differs from those of projector synesthetes but also to those of non-synesthetes.

Placing the difference at the level of the ink-naming and retrieval processes themselves has indeed important consequences regarding how associator synesthetes differ from non-synesthetes. The presence of congruency effects the ink-naming task is well documented as reflecting the presence of a synesthetic experience (Dixon et al., 2000; Elias et al., 2003; Mattingley et al., 2001; Nikolić et al., 2007; Odgaard et al., 1999). Grapheme-color synesthetes were then further sub-divided between associators and projectors, based on their opposite patterns on the ink-naming and retrieval synesthesia Stroop task (Dixon et al., 2004). However, the performance of synesthetes has never been compared to those of non-synesthete controls in the retrieval synesthesia Stroop task. In other words, it is unknown whether congruency effects in the retrieval task reflect the presence of a synesthetic experience.

MacLeod and Dunbar (1988)'s paradigm showed that it takes a rather long training for the retrieval process to be more automatized than the ink-naming one. Pritchatt (1968) designed a modified Stroop task aiming at putting into competition two retrieval processes. Participants were trained for only one of the two retrieval processes. Only a baseline and an incongruent condition were used, allowing to evaluate only interferences. The results showed that interferences where present when testing the retrieval process that had not been trained. Those results indicate that non-synesthetes may therefore should congruency effects on the retrieval task of the synesthesia Stroop, rendering this task unable to differentiate between synesthetes and non-synesthetes in the first place. In other words, the retrieval synesthesia Stroop potentially does not tap into synesthetic processes and is as such not a reliable index of the presence of a synesthetic experience.

In the present study, two experiments were conducted in order to evaluate and further understand patterns of response times and congruency effects in both the ink-naming and retrieval tasks from the synesthesia Stroop task in associator synesthetes. More precisely, three research question were investigated. First, do associator synesthetes truly show larger congruency effects in the retrieval than ink-naming task? Second, are congruency effects in the retrieval task the reflection of the presence of a synesthetic experience? Third, does the retrieval task measure the presence of synesthetic experiences that are less automatized than the stimuli color perception, or does it reflect the degree to which the retrieval process is non-automatized?

The first two research questions were investigated in Experiment 1, where a group of grapheme-color associator synesthetes and a group non-synesthete controls, who received a 3-minute training to memorize five letter-color associations, were tested on the ink-naming and retrieval synesthesia Stroop tasks. This allowed to evaluate the patterns of performances on both tasks for associator synesthetes, given the conflicting results in the past literature (Dixon et al., 2000, 2004; Hancock, 2006; Mattingley et al., 2001; Mattingley & Rich, 2004). It also allowed to investigate whether, just like for the ink-naming task, congruency effects in the retrieval task are present only in synesthetes, and therefore whether the retrieval synesthesia Stroop reflects the presence of synesthesia.

The last research question was investigated in Experiment 2, where associator synesthetes were tested on a set of memorized associations, that differed from their genuine ones. Given that congruency effects on the retrieval task were increased by testing less trained processes (Pritchatt, 1968), would memorized associations that differ from the genuine synesthetic ones also produce congruency effects in the retrieval task, showing that congruency effects on the retrieval task are a reflection of the non-automatization of the retrieval process (MacLeod & Dunbar, 1988), rather than a measure of less automatized synesthetic experiences (Dixon et al., 2004).

5.2. METHOD

5.2.1. PROCEDURE

Both experiments consisted of an ink-naming and a retrieval task. An exposure phase occurred before testing on those tasks for non-synesthete controls (Experiment 1) and synesthetes (Experiment 2).

5.2.1.1 Exposure phase

The exposure phase started with a letter appearing at the center of the screen in its associated color for 1500ms. It was then followed by a full screen in the associated color. Following Bor and colleague (2014)'s training paradigm, the "colored letter → full colored screen" sequence was shown twice in a row before moving on to the next letter. Participants were asked to simply try to remember the five letter-color pairings. Once each letter-color association had been shown 10 times in a random fashion, participants were asked to verbally recite in any order the five letter-color associations.

5.2.1.2 Ink-naming and retrieval tasks

Each trial began with a black fixation cross at the center of the screen for 500ms. The letter stimulus appeared then at the center of the screen (Arial, visual angle height 3.75°) and would remain on the screen until a vocal response was detected using the psychopy.voicekey package. Response times (RTs) were automatically extracted for each trial and a wav. file was also saved for each trial. In the ink-naming task, participants were asked to name the physical color of the stimuli, ignoring the synesthetic and/or memorized color association. In the retrieval task, participants were asked to report the color association (the synesthetic one when tested for their genuine synesthesia and the memorized one when tested for the pairings learnt during the exposure phase), ignoring the physical ink color. Each task contained 80 trials, half congruent and half incongruent intermixed, presented in a random order, and would each last for about four minutes.

5.2.2. APPARATUS

Data were collected at Aalborg University, Aarhus University, and Copenhagen University between September 2019 and September 2020, using the same LEVONO X220 Thinkpad laptop connected to a 24" BenQ screen (180 cd/m2, background color RGB (135, 135, 135)), placed 90 cm away from the participants. Vocal responses were recorded through a USB Blue Yeti desk microphone. The experiment was programmed and run with Psychopy Builder (Peirce et al., 2019).

5.2.3. STIMULI

5.2.3.1 Memorized associations for non-synesthetes (Experiment 1)

All non-synesthete participants were exposed and tested for the same five letter-color associations, shown in Fig. 5-1. The associated colors were each a different focal colors (Berlin & Kay, 1969) and the five letters were not initials of Danish color words. In the congruent condition, the letters were shown in the same color as during the exposure phase, as shown in Fig. 5-1. In the incongruent condition, each letter was shown an equal number of times in each of the four other colors (e.g., J was shown in green, blue, purple and red).

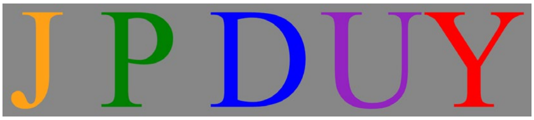

Figure 5-1 Letter-color associations to be remembered by control participants.

5.2.3.2 Genuine synesthetic stimuli (Experiment 1)

For each synesthete participant, five letters with a consistency score below the synesthesia threshold (Rothen, Seth, et al., 2013) and of different focal colors (Berlin & Kay, 1969) were selected. Furthermore, each letter stimuli could not be the initial of a color word in Danish. The top panel of Fig. 5-2 shows the letters selected for synesthete S09. In the congruent condition, the letters were shown in their synesthetic color, as shown on the top panel of Fig. 5-2. In the incongruent condition, each letter was shown an equal number of times in each of the four other colors (e.g., for synesthete S09, F was shown an equal number of times in green, blue, orange and white).

Figure 5-2 Example of letter stimuli for a synesthete participant.
The top panel represents five genuine synesthetic associations selected. The bottom panel shows five letter-color associations created that clash with the synesthete's perceptual experience and asked to be remembered.

5.2.3.3 Memorized associations for synesthetes (Experiment 2)

For each synesthete participant, the colors of the five letters used as stimuli to test for their genuine synesthesia (Experiment 2) were paired to five new letters, forming letter-color pairs that are contrary to their genuine synesthetic associations (e.g., for synesthete S09 the synesthetic color of the letter K is gray but they were asked to memorize that it was red). Here again, each letter stimuli could not be the initial of a color word in Danish. The bottom panel of Fig. 5-2 shows the letter-color associations created for synesthete S09. The congruent and incongruent conditions were built similarly as for non-synesthete controls in Experiment 1, meaning that in the congruent condition the letters were shown in the same color as during the exposure phase, as shown on the bottom panel of Fig. 5-2, and in the incongruent condition each letter was shown in each of the four other colors (e.g., for synesthete S09, K was shown an equal number of times in green, blue, orange and white).

5.2.4. PARTICIPANTS

An a priori power analysis, run on G*Power 3.1.9.4 (Faul et al., 2009) with an alpha of .05 and a desired power of .80, determined that 15 participants were needed based on the mean congruency effect found by Dixon and colleagues (2004) in associator synesthetes on the ink-naming task.

Eighteen synesthetes and 18 non-synesthetes were recruited. Synesthete participants completed an in-lab synesthesia screening (Ásgeirsson et al., 2015; Eagleman et al., 2007) in order to confirm their letter-color associations. All synesthete participants reported experiencing the concurrent colors in their mind's eye.

Non-synesthete and synesthete participants were matched for age (M_{SYN}= 30,78; SD_{SYN}=9,32; M_{CONT}=30; SD_{CONT}=10,42) and gender (14 females and four males in both groups). All non-synesthetes confirmed having never experienced any form of grapheme-color synesthesia (i.e., perceptual color responses to graphemes, phonemes, or words). All participants were native speakers of Danish (35 participants) or Swedish (one synesthete) and performed the task in Danish. The same synesthete participants took part in Experiment 1 and Experiment 2.

5.3. EXPERIMENT 1 - RESULTS

RTs above 2500ms were discarded as reflecting the microphone failing to pick up the participant's first answer (1.5% of the data). Trials resulting in empty wav. files were also discarded (5.6% of the remaining data), as well as trials with non-accurate answers (1.6% of the remaining data). RTs below 400ms were manually checked and corrected if needed (1.1% of the remaining data). One non-synesthete participant failed to repeat the five letter-color associations to be remembered during the exposure phase and was therefore removed from the analysis.

5.3.1. ACCURACY ANALYSIS

A 2x2x2 mixed ANOVA was run on accuracy percentages as a function of Group (synesthetes vs. non-synesthete controls), Task (ink-naming vs. retrieval) and Congruency (congruent vs. incongruent). A main effect of Congruency ($F(1,33) =6.63, p = .015, \eta_p^2 = .167$) appeared, however, accuracy was overall still high on both congruency conditions (M_{CONG} = 99%; SD_{CONG} = 2% ; M_{INC} = 98%; SD_{INC} = 4%). A significant interaction of Task and Group ($F(1,33) =4.91, p = .034, \eta_p^2 = .129$) was also present, but none of the post-hoc pairwise comparisons survived Bonferroni correction. All other main effects and interactions were not significant (All *p*s > .05).

5.3.2. RESPONSE TIME ANALYSIS

A 2x2x2 mixed ANOVA run on RTs as a function of Group (synesthetes vs. non-synesthete controls), Task (ink-naming vs. retrieval) and Congruency (congruent vs. incongruent) revealed a significant main effect of Task ($F(1,33)$ =7.05, p = .012, η_p^2 = .176), and of Congruency ($F(1,33)$ =68.69, p < .001, η_p^2 = .675). No main effect of Group was found ($F(1,33)$ =0.15, p = .7, η_p^2 = .005).
An interaction of Task and Group ($F(1,33)$ =12.92, p < .001, η_p^2 = .281) was found, as well as an interaction of Congruency and Group ($F(1,33)$ =5.48, p = .025, η_p^2 = .143). However, no interaction of Task and Congruency ($F(1,33)$ =0.78, p = .382, η_p^2 = .023) was found.
Finally a three-way interaction of Congruency, Task and Group ($F(1,33)$ =15.82, p < .001, η_p^2 = .324) was found. Bonferroni-corrected pairwise comparisons confirmed the presence of a congruency effect in the ink-naming task for synesthete group (M_{CONG} = 812ms; M_{INC} = 1016ms; p < .001), but not in the non-synesthete group (M_{CONG} = 790ms; M_{INC} = 830ms; p = 1). Regarding the retrieval task, both the synesthete (M_{CONG} = 842 ms; M_{INC} = 923ms) and non-synesthete (M_{CONG} = 962 ms; M_{INC} = 1081ms) groups showed a significant congruency effect (all ps < .001). RTs across groups and conditions are shown in Fig. 5-3.

5.3.3. CONGRUENCY EFFECT ANALYSIS

Congruency effects were computed as the difference between mean response times in the incongruent and congruent conditions for each task and participant.

A 2x2 mixed ANOVA was run on the congruency effects as a function of Group (synesthetes vs. non-synesthete controls), Task (ink-naming vs. retrieval). No main effect of Task was found ($F(1,33)$ =0.78, p = .382, η_p^2 = .023). A main effect of Group ($F(1,33)$ =5.48, p = .025, η_p^2 = .143) was present, as well as an interaction of Task and Group ($F(1,33)$ =15.82, p < .001, η_p^2 = .324) was present. Bonferroni-corrected pairwise comparisons showed that the congruency effect in the ink-naming task was significantly larger in the synesthete than in the non-synesthete group (M_{SYN} = 204ms; M_{NON-S} = 40ms; p = .011). In the retrieval task, on the other hand, no significant difference appeared between groups (M_{SYN} = 81ms; M_{NON-S} = 119ms; p = .378). Furthermore, in the synesthete group the congruency effect was significantly larger in the ink-naming than in the retrieval task (M_{INK} = 204ms; M_{RET} = 81ms; p = .008). In the non-synesthete group, on the other hand the difference between task was not significant (M_{INK} = 40ms; M_{RET} = 119ms; p = .231).

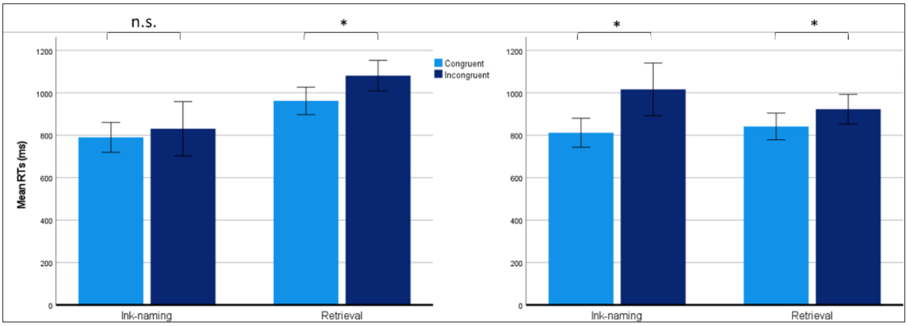

Figure 5-3 Mean response times in ms on the ink-naming and retrieval tasks in the congruent and incongruent conditions between groups.
Non-synesthete control group tested for memorized associations are shown on the left panel and synesthete group tested for their genuine associations are shown on the right panel. Asterisks denote statistically significant congruency effects at p < .05 and error bars represent 95% CI.

5.4. EXPERIMENT 2 - RESULTS

RTs above 2500ms were discarded as reflecting the microphone failing to pick up the participant's first answer (1.7% of the data). Trials resulting in empty wav. files were also discarded (4.7% of the remaining data), as well as trials with non-accurate answers (2.5% of the remaining data). RTs below 400ms were manually checked and corrected if needed (1.1% of the remaining data). One non-synesthete participant failed to repeat the five letter-color associations to be remembered during the exposure phase and was therefore removed from the analysis.

5.4.1. ACCURACY ANALYSIS

A 2x2 repeated measure ANOVA was run on accuracy percentages as a function of Task (ink-naming vs. retrieval) and Congruency (congruent vs. incongruent). No main effect of Task ($F(1,15) = 0.05$, $p = .833$, $\eta_p^2 = .003$) nor Congruency ($F(1,15) = 2.03$, $p = .174$, $\eta_p^2 = .119$) appeared, as well as no interaction of Congruency and Task ($F(1,15) = 0.55$, $p = .471$, $\eta_p^2 = .035$). Overall accuracy was high (M = 97%).

5.4.2. RESPONSE TIME ANALYSIS

A 2x2 mixed ANOVA run on RTs as a function of Task (ink-naming vs. retrieval) and Congruency (congruent vs. incongruent) revealed a significant main effect of Task ($F(1,15) = 248.1$, $p < .001$, $\eta_p^2 = .943$), and of Congruency ($F(1,15) = 43.7$, $p < .001$, $\eta_p^2 = .744$).

An interaction of Task and Congruency ($F(1,15) = 40.5$, $p < .001$, $\eta_p^2 = .73$) was also found. Bonferroni-corrected pairwise comparisons revealed the presence of a congruency effect in the retrieval task ($M_{CONG} = 1012$ms; $M_{INC} = 1150$ms; $p < .001$), but not in the ink-naming task (M_{CONG} = 784ms; M_{INC} = 812ms; *p* = .133). RTs across conditions are shown in Fig. 5-4.

5.4.3. CONGRUENCY EFFECT ANALYSIS

A paired sample t-test run on the congruency effects as a function of Task (ink-naming vs. retrieval) showed that the congruency effect was larger in the retrieval task than in the ink-naming task (M_{INK} = 28ms; M_{RET} = 138ms; *t*(15) = 6.36, *p* < .001, *d* = 1.59).

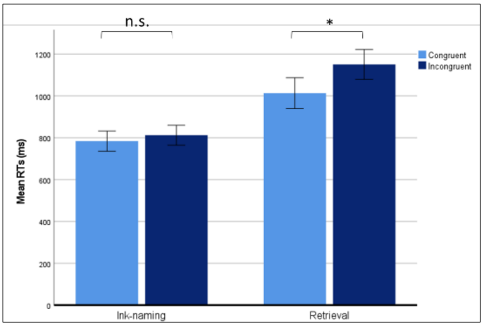

Figure 5-4 Mean response times in ms on the ink-naming and retrieval tasks in the congruent and incongruent conditions for synesthetes tested on memorized associations.
Asterisks denote statistically significant congruency effects at p < .05 and error bars represent 95% CI.

5.5. DISCUSSION

In experiment 1, a group of associator synesthetes and a group of non-synesthete controls were tested on both the ink-naming and retrieval tasks of the synesthesia variation of the Stroop task. The synesthete group was tested for their genuine associations, while the non-synesthete controls were asked to briefly memorize a set of five letter-color associations, in order to be able to perform the retrieval task.

The results showed, first, that a congruency effect was present in the ink-naming task in the synesthete group but not in the non-synesthete control group. Second, a congruency effect was present in both groups in the retrieval task. Finally, the associator synesthete group showed larger congruency effects in the ink-naming than in the retrieval task.

In experiment 2, associator synesthetes were tested on both the ink-naming and retrieval tasks of the synesthesia Stroop for a set of letter-color pairs that was not their synesthetic ones and that they had been asked to memorize. A significant congruency effect appeared in the retrieval task, but not in the ink-naming task.

5.5.1. COMPARISON TO PREVIOUS RESULTS FROM ASSOCIATOR SYNESTHETES

Dixon and colleagues (2004)'s original study described opposite performances from associator and projector synesthetes in the ink-naming and retrieval tasks and claimed that while projectors answered slower and showed larger congruency effects in the ink-naming than retrieval task, associators answered slower and showed larger congruency effects in the retrieval than ink-naming task. Nevertheless, the results from their associator group were above the significant statistical threshold and could at best only show a trend toward different RTs and congruency effects between tasks in this sub-group of synesthetes.

The present study paints a different picture of associator synesthetes' performances on the synesthesia Stroop (Experiment 1). We found indeed that associator synesthetes were subject to a congruency effect in both the ink-naming and retrieval tasks, and that the congruency effect was larger in the ink-naming (204ms) than retrieval task (81ms).

Although our results contradict Dixon and colleagues (2004)'s claim, they are quite in line with previous results that found a significant congruency effect in the ink-naming task in associator synesthetes (Hancock, 2006; Levy et al., 2017; Mattingley et al., 2001; Nikolić et al., 2007). Mattingley and colleagues (2001) found that 12 of the 15 associator participants tested had RTs mathematically superior in the incongruent than congruent condition (Mattingley & Rich, 2004). Similarly, in our present study, 17 of the 18 associator synesthetes tested also followed this pattern.

The performance of associator synesthetes on the retrieval task has though barely been tested since Dixon and colleagues (2004)'s original study, and when the task was used, no results were provided regarding congruency effects in this task particularly (Ward et al., 2007).

5.5.2. LESSONS FROM INCLUDING CONTROLS TO THE RETRIEVAL TASK

While synesthetes' performances have been compared to non-synesthete controls on the ink-naming task in the past (Dixon et al., 2000; Elias et al., 2003; Mattingley et al., 2001), it has not been the case for the retrieval task. As expected from those previous studies, when tested for memorized associations, neither non-synesthetes (Experiment 1) nor synesthetes (Experiment 2) were subject to any congruency effect in the ink-naming task. However, both groups produced a congruency effect in the retrieval task. Importantly, in the case of synesthetes, in Experiment 2, the memorized associations contradicted their synesthetic color experience (e.g., regardless of the color in which it appeared, upon viewing the stimulus K synesthete S09 had to answer "red" as per the exposure phase, although their synesthetic color for the letter K was gray). Critically, synesthetes tested for their genuine associations (Experiment 1) also produced a congruency on the retrieval task (e.g., regardless of the color in which it appeared, upon viewing the stimulus F synesthete S09 had to answer “red”, as their synesthetic color for the letter F is red).

Our exposure phase lasted only three minutes and consisted of only 10 repetitions of each letter-color pairs, and none of the non-synesthete nor synesthete participants reported experiencing the memorized colors physically. Our results therefore show that the mere presence of a congruency effect in this retrieval task is not a sign of the presence of an automatic synesthetic experience. Indeed, the congruency effect in the retrieval task was even larger when synesthetes had to retrieve memorized associations that contradict their synesthetic ones (138ms) than when tested for their genuine ones (81ms). Instead, it seems to be a measure of the degree to which the retrieval process is less automatized than the ink-naming process, as proposed by MacLeod and Dunbar (1988). In this sense, our results show that the less genuine the association, and therefore the less automatized the retrieval of this association, the larger the congruency effect on the retrieval task of the synesthesia Stroop. Namely, in Experiment 2 synesthetes had to ignore both their genuine synesthetic color and the displayed color on the screen to be able to retrieve the memorized associations, which produced a large congruency effect (138ms) in the retrieval task, but no congruency effect in the ink-naming task. In Experiment 1, non-synesthete controls had to ignore only the displayed color on the screen to be able to retrieve the memorized associations. They also produced a significant congruency effect in the retrieval task (119ms), although slightly smaller than in synesthetes from Experiment 2, and again no congruency effect in the ink-naming task. In Experiment 1, synesthetes also had to ignore only the displayed color on the screen, but this time it is their genuine associations they had to retrieve. They produced also a significant congruency effect in the retrieval task (81ms), but this time an even larger congruency effect in the ink-naming task (204) was also presented. Differences in RTs in the ink-naming and retrieval tasks are also in line with MacLeod and Dunbar (1988)’s proposal for congruency effects on the retrieval task reflecting a continuum of automaticity of the retrieval process compared to the ink-naming one. Namely, in Experiment 2, synesthetes took significantly longer (284ms more) to retrieve the memorized color than to name the ink color. In Experiment 1, while non-synesthete controls also took longer (211ms more) to retrieve the memorized color than to name the ink color, for synesthetes there was no significant difference in RTs for retrieving the genuine synesthetic color and naming the ink color (31ms faster for naming the ink color). Following MacLeod and Dunbar (1988)’s continuum of automaticity of the ink-naming and retrieval processes, while the ink-naming process is more automatized than the retrieval one for memorized associations in both synesthetes and non-synesthete controls, both processes seem equally automatized for genuine synesthetic color experiences in associator synesthetes.

Finally, our results are in line with Pritchatt (1968) who found that congruency effects were larger for a retrieval task that were the least trained. It can be expected that synesthetes are more experts in retrieving their own synesthetic experiences than the letter-color associations they were given only 3 minutes to remember. In other words, the more difficult the retrieval process, the larger the congruency effect on the retrieval task.

5.5.3. REEVALUATING THE PROJECTOR/ASSOCIATOR DISTINCTION

Dixon and colleagues (2004)'s study which showed opposite patterns of performance for associator and projector synesthetes on the ink-naming and retrieval tasks of the synesthesia variation of the Stroop task has had great influence on synesthesia research. It solidified the idea that, first, two main phenomenological patterns existed in grapheme-color synesthetes, and second, that these different experiences resulted in opposite performances using an indirect method. Nevertheless, the associator/projector distinction may not be as straightforward as drawn by Dixon and colleagues (2004).

First of all, performances on the synesthesia Stroop by both associators and projectors that are not in line with Dixon and colleagues (2004)'s results can already be found in the literature (Hancock, 2006; Laeng et al., 2011; Levy et al., 2017; Mattingley et al., 2001; Mattingley & Rich, 2004; Nikolić et al., 2007; Rothen, Tsakanikos, et al., 2013). Moreover, the projector/associator distinction may not reflect the full picture of the synesthetic experience. It seems indeed that while questionnaires (e.g., RSPA: Rouw & Scholte, 2007 or ISEQ: Skelton et al., 2009) allow to sort out most individuals into the projector or associator groups, in practice, they also fail to classify a non-neglectable number of synesthetes (e.g., see Hamada et al. (2017) where out of 26 grapheme-color synesthetes, the ISEQ managed to sort 15 as associators, 4 as projectors, but 7 were not able to be classified as either). Testing the reliability of the RSPA and ISEQ, respectively 11.4% and 18.3% of synesthetes could not be clearly classified as either associator or projector (Anderson & Ward, 2015). More specifically, Anderson & Ward (2015) found that out of 175 synesthetes taking the RSPA questionnaire, 12 reported both internal and external experiences, and eight reported neither. The ISEQ questionnaire was not more efficient, as 10 synesthetes reported both internal and external experiences, and 22 reported neither. The authors therefore argued for a "dual locus" subgroup, containing individuals with both internal and external experiences (Anderson & Ward, 2015). This third category, nevertheless, still leaves out 4.6% to 12.6% of the synesthetes tested (Anderson & Ward, 2015) who reported neither internal nor external experiences.

Rothen, Tsakanikos and colleagues (2013) conducted a factor analysis on a set of probing questions and found four determining factors: localization, automaticity, deliberate use, and longitudinal change. The localization factor was correlated to synesthesia Stroop RTs, where high localization (i.e., the concurrent experience has a specific location in space, either internal or external) led to faster RTs in both the ink-naming and retrieval tasks than experiences with low localization (i.e., the concurrent experience does not have a specific location in space). These results demonstrate that synesthesia Stroop results can support other categorizations of the synesthetic experience, indicating that the associator/projector classification may not be the most important phenomenological trait to distinguish between synesthetes.

The most extensive training study to date aiming at inducing synesthesia in adults have used the synesthesia Stroop to assess the success of the training (Bor et al., 2014). Participants' performance post-training on both the ink-naming and the retrieval tasks, which were not compared to controls, showed large congruency effects. Out of the 14 participants trained, eight reported perceptual color experiences, in their mind, post-training, which though disappeared after three months. Although phenomenologically resembling associator synesthetes, the authors did not find any correlation between the phenomenological reports and results on neither the ink-naming nor retrieval task, further indicating that the presence of a congruency effect in the retrieval task is not necessarily the reflection of a reported synesthetic experience. This lack of correlation in the ink-naming task is, however, surprising as past studies have consistently found that the ink-naming task produced different responses depending on whether a synesthetic experience was present or not (Dixon et al., 2000; Elias et al., 2003; Mattingley et al., 2001). Critically though, only the letter-color pairs built by Bor and colleagues (2014) in order to mimic associations commonly reported by both synesthetes and non-synesthetes (Simner et al., 2005) led to a congruency effect in the ink-naming task, while the random pairs did not. The next chapter will explore why only letter-color associations that are shared between synesthetes and non-synesthetes can be trained to gain synesthesia-like qualities.

CHAPTER 6. THE EFFECT OF ORTHOGRAPHIC CUEING

6.1. INTRODUCTION

In the decade following Dixon and colleagues (2004)'s study demonstrating behavioral differences based on phenomenological variations of synesthesia, the synesthesia Stroop was applied to studies attempting to train non-synesthetes to acquire synesthesia. In order to understand how synesthesia emerges, researchers have long questioned whether non-synesthete adults can be taught synesthesia. Here again, studies focused on grapheme-color synesthesia.

Over a span of ten years, several studies have measured congruency effects in a synesthesia Stroop task of non-synesthetes who received a grapheme-color training. The longest training of all might be for a cross-stitcher participant who came to learn digit-color associations due to the eight years of practicing her hobby (Elias et al., 2003). In the pattern directions she was following, each thread color was referred to using a given number. Upon testing on an ink-naming task, she displayed a congruency effect, as did a grapheme-color synesthete also tested, but not controls.
Later, 20 non-synesthetes were trained 10 minutes a day for seven days to learn four letter-color associations (Meier & Rothen, 2009). This training was enough to produce a congruency effect post-training in an ink-naming task. Critically however, the participants did not show any conditioned response, measured using skin conductance response, while synesthetes were previously found to do so (Meier & Rothen, 2007). The same synesthesia Stroop paradigm was used on 17 non-synesthetes who underwent a letter-color training consisting in reading books in which four letter were consistently colored (Colizoli et al., 2012). Here again, participants showed a congruency effect post-training only.
The training studies mentioned above featured an explicit training, where participants were aware of the designed letter-color pairs. A synesthesia Stroop was therefore used to assess whether implicit pairings could also be acquired and would result in congruency effects in an ink-naming task (Kusnir & Thut, 2012). Here, two 45-minute sessions of performing an unrelated task (i.e., a visual search task) were hoped to cause statistical probability learning for two letter-color associations in 27 non-synesthetes. A post-training button-press version of the synesthesia Stroop was used, instead of the usual vocal response onset. Implicit learning did not produce any congruency effect for the trained non-synesthetes. The lack of congruency effect might not be due to the change in response modality since three grapheme-color synesthetes tested using the same button-press paradigm did show a congruency effect, although about ten times lower than the one measured commonly using vocal respond onset (Kusnir & Thut, 2012).

Finally, the most comprehensive training study to date used an explicit training paradigm (Bor et al., 2014). Thirteen letter-color pairings were trained over the span of nine weeks, five days a week, 30 minutes per session (a total of 22.5 hours of training in the lab + homework using books with colored letters). Thirteen different training tasks were used, increasing in difficulty. The letter-color pairings comprised seven orthographic pairings (called "semantic associations" in the original paper), where the letter was paired with the color name it is the initial of (e.g., B was paired with blue), and six non-orthographic pairings, where the letter was paired with a color it is not the initial of (e.g., Q was paired with purple). An ink-naming synesthesia Stroop was performed pre-, mid- and post-training. A congruency effect was present at all three stages of training for the orthographic associations and increased at each stage. No congruency effect was present, however, at any stage for the non-orthographic pairings. A retrieval synesthesia Stroop was performed post-training only and both orthographic and non-orthographic pairings caused a congruency effect. A follow-up ink-naming synesthesia Stroop was also performed three months after training, which showed here again a congruency effect for the orthographic pairings but not for the non-orthographic ones. The authors argued that the orthographic pairings showed a more consistent congruency effect, even before training, because those pairings were purposely chosen to reflect genuine synesthetic associations. It has indeed been previously shown that synesthetes have a tendency to form associations based on color name initials (Rich et al., 2005; Simner et al., 2005). Critically, non-synesthetes tend also to report such preferences when asked to pick a color for a letter (Simner et al., 2005), denoting possible cross-modal correspondence between letters and colors. The presence of a congruency effect for such pairings pre-training may have therefore reflected non-synesthetes' intuitive associations, despite their lack of perceptual color experiences (Bor et al., 2014).

Nevertheless, in a modified Stroop task, Regan (1978) had shown that the letters R, B, and G were enough to create both an interference and a facilitation compared to colorless baseline letters in an ink-naming task. The study aimed at demonstrating that the initial letter of a color name was enough to prime a full color word (e.g., R primes "red"), causing an orthographic cueing, relying on the original Stroop effect (Stroop, 1935). Results from Regan (1978) point out to the possibility that the congruency effects found in the ink-naming task for orthographic associations by Bor and colleagues (2014) could simply be due to orthographic cueing. However, Regan (1978)'s paradigm was quite limited, as it contained only three color word initials, and only featured an ink-naming task. No reversed task (i.e., reading task) nor original Stroop task using full color words were used, to allow to fully evaluate the directionality of the effect, nor to make direct comparisons between orthographic cueing and the reading process.

In the present study, the paradigm used by Regan (1978) was first extended to more color word initials to replicate the results showing that orthographic cueing is enough to interfere with the ink-naming process. Second, a reversed task was also included, where participants were asked to retrieve the color name that begins with the displayed letter, in order to evaluate whether the stimuli color can also interfere with orthographic cueing. Both a group of synesthetes, whose letter-color associations are not based on orthographic associations, and of non-synesthetes were tested, to probe whether orthographic cueing is stronger than the competition caused by the synesthetic experience, and therefore whether orthographic cueing is enough to cause a congruency effect, emulating results normally found in synesthetes in the ink-naming task. Finally, an original Stroop task, using full color words, was also run, in order to evaluate whether performances differ when using full color words and only relying on orthographic cueing.

6.2. METHOD

6.2.1. PROCEDURE

The experiment consisted of four different tasks completed by both grapheme-color synesthete and non-synesthete participants. The same participants who participated in Experiment 1 and 2 of Chapter 5 took part in the experiment present here.

6.2.1.1 Word Stroop – ink-naming and reading tasks

At the beginning of each trial a black fixation cross appeared at the center of the screen for 500ms. The color word stimulus was then displayed at the center of the screen (Arial, visual angle height 3.75°) and until detection of a vocal response using the psychopy.voicekey package. Both response times (RTs) and a wav. recording of each trial were automatically saved. In the ink-naming task, participants had to name the physical color of the color word, ignoring the meaning of the color word. Oppositely, in the reading task, participants had to read the word written on the screen, ignoring its physical color. Each task was made of 80 trials (50% congruent - 50% incongruent trials intermixed) randomized. Each task took about four minutes to complete.

6.2.1.2 Letter Stroop – ink-naming and retrieval tasks

The procedure was similar to the word Stroop described above, with the exception that now only the initial letters of the color words were presented. In the ink-naming task, participants were asked to name the ink color displayed, ignoring what color word starts with the letter shown. In the retrieval task, participants were asked to name the color word that starts with the letter displayed, ignoring its physical color.

6.2.2. APPARATUS

Data were collected at three different locations (Aalborg University, Aarhus University, and Copenhagen University) between September 2019 and September 2020, using the same LEVONO X220 Thinkpad laptop connected to a 24” BenQ screen (180 cd/m2, background color RGB (135, 135, 135)), placed 90 cm away from the participants, and USB Blue Yeti desk microphone. The experiment was programmed and run with Psychopy Builder (Peirce et al., 2019).

6.2.3. STIMULI

6.2.3.1 Stimuli for synesthete participants

For each synesthete participant, the five colors that had been used in the experiment presented in Chapter 5 were also used here. In the Word Stroop, the full color word was written out (left-hand side of Fig. 6-1 shows the word stimuli for synesthete S09). In the Letter Stroop, the corresponding initial letters were shown (right-hand side of Fig. 6-1 shows the letters stimuli for synesthete S09). The synesthetic colors of the letter stimuli used in the Letter Stroop tasks for every synesthete participant were not based on orthographic associations (e.g., for synesthete S09 the genuine synesthetic letter-color associations of the letter stimuli selected are R-dark blue, G-blue, B-yellow, O-black, H-peach).

Figure 6-1 Word and letter stimuli for a synesthete participant.
The left panel shows the color word stimuli used for the Word Stroop tasks (from top to bottom: red, green, blue, orange, white), based on the colors selected for the experiment described in Chapter 5. The right panel shows their corresponding initial letter, used for the Letter Stroop tasks.

6.2.3.2 Stimuli for non-synesthete participants

The same set of stimuli were used for every control participant, here also based on the colors used in the experiment presented in Chapter 5. The full color words used in the Word Stroop are shown on the left-hand side of Fig. 6-2, and the corresponding letter stimuli are shown on the right-hand side of Fig. 6-2.

Figure 6-2 Word and letter stimuli for control participants.
The left panel shows the color word stimuli used for the Word Stroop tasks (from top to bottom: orange, green, blue, purple, red), based on the colors selected for the experiment described in Chapter 5. The right panel shows their corresponding initial letter, used for the Letter Stroop tasks.

6.2.4. PARTICIPANTS

Eighteen synesthetes and 18 non-synesthetes took part in all four tasks. Synesthete participants' letter-color associations were confirmed using an in-lab synesthesia screening (Ásgeirsson et al., 2015; Eagleman et al., 2007). All synesthetes reported experiencing the concurrent colors in their mind's eye.

Non-synesthete and synesthete participants were matched for age (M_{syn}= 30,78; SD_{syn}=9,32; M_{cont}=30; SD_{cont}=10,42) and gender (14 females and four males in both groups). All non-synesthetes participants confirmed having never experienced any form of grapheme-color synesthesia (perceptual color response to graphemes, phonemes, or words). All participants were native speakers of Danish (35 participants) or Swedish (one synesthete) and performed the task in Danish.

6.3. RESULTS

Extracted RTs above 2500ms were discarded (0.7% of the data) as reflecting the microphone not picking up the participant's answer. Empty recordings (3.8% of the remaining data) and non-accurate answers (2% of the remaining data) were also discarded. Automatically extracted RTs below 400ms were manually checked and corrected (1.5% of the remaining data).

A sensitivity analysis ran in G*Power 3.1.9.4 (RRID:SCR_013726) indicated that our sample size allowed to detect a minimum effect size of η_p^2 = .038 with a power of 95% and an alpha of .05.

6.3.1. RESPONSE TIME ANALYSIS

A 2x4x2 mixed ANOVA was run on the RTs as a function of Group (non-synesthete vs. synesthete), Task (word-ink-naming vs. letter-ink-naming vs. letter-retrieval vs. word-reading) and Congruency (congruent vs. incongruent). Huynh-Feldt corrected *p*-values are reported in the subsequent analysis due to Maulchy's test of sphericity showing a violation of the sphericity assumption in the Task condition and in the interaction of Task and Congruency. Mean RTs across Tasks, Congruency conditions and Groups are shown in Fig. 6-3.

A main effect of Congruency (F(1,34) = 186.79, $p < .001$, $\eta_p^2 = .846$) showed that the congruent condition was answered significantly faster (699ms) than the incongruent one (789ms). A main effect of Task (F(3,102) = 47.32, p < .001, $\eta_p^2 = .582$) was also found and Bonferroni-corrected pairwise comparisons revealed significant differences between all tasks (with *p*s < .001), except between the ink-naming tasks for word and letter stimuli ($p > .154$) (word-ink-naming: 869ms; letter-ink-naming: 807ms; letter-retrieval: 690ms; word-reading: 611ms). No main effect of Group was present (F(1,34) = 0.01, $p = .916$, $\eta_p^2 < .000$).

No interaction of Congruency and Group (F(1,34) = 0.03, $p = .855$, $\eta_p^2 = .001$) nor of Task and Group (F(3,34) = 1.14, $p = .333$, $\eta_p^2 = .033$) were present. An interaction of Congruency and Task (F(3,102) = 1.22, $p < .001$, $\eta_p^2 = .609$) was found and Bonferroni-corrected pairwise comparisons revealed the presence of a congruency effect in the word-ink-naming (148ms; $p < .001$), letter-ink-naming (157ms; $p < .001$), word-reading (19ms; $p = .008$) and letter-retrieval (35ms; $p < .001$) tasks. Finally, no three-way interaction of Congruency, Task and Group (F(3,34) = 2.83, $p = .051$, $\eta_p^2 = .077$) was found.

6.3.2. CONGRUENCY EFFECT ANALYSIS

Congruency effects are computed as the difference between mean RTs in the incongruent and congruent conditions, for each task and participants.

A 2x4 mixed ANOVA was run on the RTs as a function of Group (non-synesthete vs. synesthete) and Task (word-ink-naming vs. letter-ink-naming vs. letter-retrieval vs. word-reading). Huynh-Feldt corrected *p*-values are reported in the subsequent analysis due to Maulchy's test of sphericity showing a violation of the sphericity assumption in the Task conditions.

A main effect of Task (F(3,34) = 52.87, $p < .001$, $\eta_p^2 = .609$) was found and Bonferroni-corrected pairwise comparisons revealed that both ink-naming tasks had congruency effects not significantly different from each other ($p = 1$), as did the word-reading and letter-retrieval tasks ($p = .772$), all other comparisons were significant, with $p < .001$. No main effect of Group was present (F(1,34) = 0.034, $p = .855$, $\eta_p^2 = .001$).

Finally, no significant interaction of Task and Group (F(3,34) = 2.83, $p = .051$, $\eta_p^2 = .077$) was found.

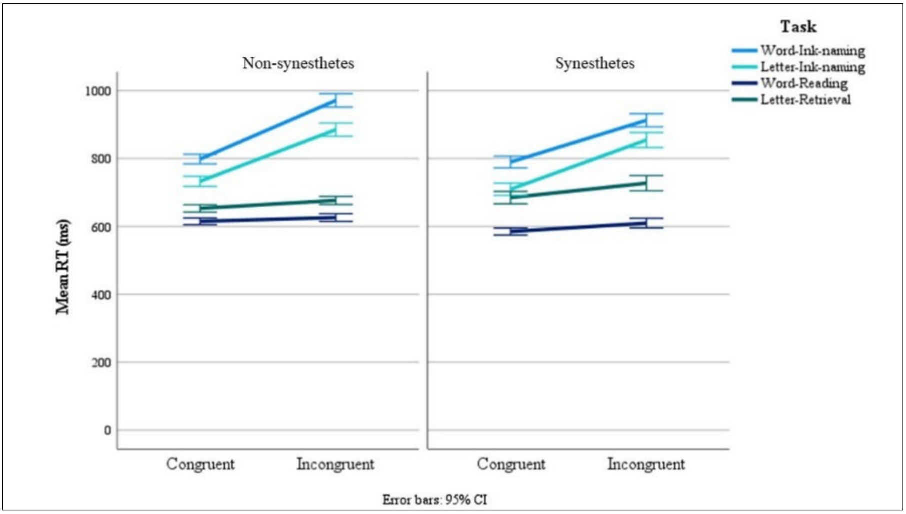

Figure 6-3 Mean response times in ms on the Word and Letter Stroops for the ink-naming, reading and retrieval tasks in the congruent and incongruent conditions for the synesthete and non-synesthete groups.

6.4. DISCUSSION

A group of non-synesthete participants were tested on a set of Stroop tasks, using stimuli consisting of either full color words or only the initial letter of those color words, shown in a color either congruent or incongruent. A congruency effect was found in each task, namely, when participants had to name the displayed color of the two types of stimuli, when having to read the color words and when retrieving the color name that starts with the displayed letter. Furthermore, two groups of significantly different congruency effects were found, with on one side the congruency effects in the ink-naming tasks both for full color word and initial letters, and on the other side, congruency effects in the reading and color word retrieval tasks. The group of grapheme-color synesthetes, whose concurrent colors were not based on orthographic associations, showed the same patterns of congruency effects as the non-synesthete group.

6.4.1. COMPARISON TO PREVIOUS RESULTS FROM GRAPHEME-COLOR TRAINING STUDIES

Bor and colleagues (2014)'s study stands out from previous ones, first due to the extensive length of the training, and because the congruency effect remained in the ink-naming task at least three months after the training ended. However, upon closer examination, one can see that the congruency effect was only present in letter-colors pairs created based on orthography. Furthermore, participants already showed a congruency effect for those pairs before the training even started. The non-orthographic pairs, on the other hand, never showed any congruency effect in the ink-naming task, at any point of training. One can therefore wonder what aspect of orthographic pairings makes them particular.

An optimistic interpretation would be that, since orthographic pairings are commonly reported in both grapheme-color synesthetes and non-synesthetes (Rich et al., 2005; Simner et al., 2005), the congruency effect found pre-training reflected this intuitive preference, and training only reinforced associations previously present. However, a study by Regan (1978) showed that initial letters of color words were enough to produce a congruency effect in the ink-naming task, pointing out to the possibility that the congruency effects found for trained orthographic pairings were just a Stoop effect, which got reinforced through training.

Our results replicated Regan (1978)'s results, and also showed that congruency effects in the ink-naming task do not significantly differ whether participants are shown full color words or only their initial letters. Critically, grapheme-color synesthetes, for whom the concurrent color was not orthography-based, also showed the same effect. In other words, the ink-naming task for orthographic letter-color pairs do not seem to rely on synesthetic mechanisms. In fact, the processes involved seem even more automatic that the synesthetic experience. Our results show therefore that the congruency effect found in the ink-naming task by Bor and colleagues (2014) was potentially greatly confounded by orthographic cueing processes, and therefore does not reliably show that participants have managed to acquire synesthesia as adults. Furthermore, their non-orthographic associations did not produce any congruency effect at any stage of training (Bor et al., 2014). As showed in our present study, orthographic cueing causes the initial letter of color words to automatically prompt the full color name, and this process is already an automatic one without any training needed. As training goes on, this orthographic cueing may get reinforced. The fact that the congruency effect in the ink-naming task increased as training went on (Bor et al., 2014) could indicate this strengthening of orthographic cueing. In other words, each time the letter "R" is viewed in red during training, participants have no reason to suppress the orthographic cueing. The buildup of a verbal competition for orthography-based pairings might therefore have been a much straightforward process than building up verbal competition for non-orthographic ones, possibly showing that the retrieval process can get reinforced for a limited number of items at a time, and that stimuli that are the easiest to build automatization for are favored. Further research is of course needed to evaluate this possibility.

6.4.2. LESSONS FROM ORTHOGRAPHY-BASED CONGRUENCY EFFECTS

In anomia patients, using the initial letter of a word to prompt word retrieval (i.e., orthographical cueing) is a frequently used technique (Best et al., 2002; Howard & Harding, 1998; Lorenz & Nickels, 2007). This method stems from the idea that initial letters facilitate full word retrieval (Bowles & Poon, 1985), relying on the orthographic-phonological conversion of the initial letter (Howard & Harding, 1998;

Lorenz & Nickels, 2007). As shown by Regan (1978), the initial letters of color words managed to prompt the full word, which resulted in a congruency effect in an ink-naming task. In other words, upon seeing the letter "R", participants were automatically prompted to say the color name "red", but when asked to instead report the stimulus color, say blue, the initial letter interferes with the ink-naming process. Importantly, while both the initial and final letters of a word have this orthographic cueing ability, the middle letters of the word do not (Arsalidou et al., 2013).

In our study, synesthetes showed this orthographic cueing effect, even when their synesthetic experiences clashed with the cued information. For synesthete S09, both letters R and G are synesthetically associated with the color blue, meaning that when shown in blue, although they were congruent to the synesthetic experience, they were incongruent to the orthographic cueing. Here, the answer "blue" was given slower than respectively "red" and "green" for the letter R and G, indicating that the orthographic cueing process, which relies on orthographic-phonological conversion, is a stronger one than the urge to name the synesthetic color perceived.

This leads to important methodological consideration for future studies aiming at investigating letter-color associations in both synesthetes and trained non-synesthetes. As shown in Chapter 5, the ink-naming task is more reliable when it comes to probing synesthetic experiences than the retrieval task. Our results here show that, nevertheless, when using an ink-naming task, orthographic cueing can be a huge confounder, and produce congruency effects that do not rely on synesthetic experiences. As such initial letters of color words should be avoided as synesthesia Stroop stimuli.

6.4.3. REEVALUATING THE PERFORMANCES OF TRAINED NON-SYNESTHETES

Other past studies aiming to train grapheme-color associations in non-synesthete adults did not use orthographic pairings (Colizoli et al., 2012; Kusnir & Thut, 2012; Meier & Rothen, 2009). While both Colizoli and colleagues (2012) and Meier & Rothen (2009) obtained a congruency effect in the synesthesia Stroop ink-naming task post-training, four to six months after training the participants could only remember on average 1.6 of the four pairs trained (Colizoli et al., 2012), or did not show any physiological conditioned response nor reported color experiences (Meier & Rothen, 2009), as normally found in synesthetes (Meier & Rothen, 2007), indicating that while some congruency effects in the ink-naming task may at time occur immediately post-training (Colizoli et al., 2012), the effect of the training quickly vanishes.

Some of the participants trained by both Colizoli and colleagues (2012) and Bor and colleagues (2014) reported a perceptual color experience post-training. However, the experience had faded away already after three month (Bor et al., 2014). Meier & Rothen (2009)'s participants did not report any color experiences post-training, despite showing a congruency effect in the ink-naming task. This prompted the authors to hypothesize that the ink-naming task tapped into the semantic level of the associations. Nevertheless, it could simply be that the letter-color synesthesia training caused an automatization of the retrieval process, which came to interfere with the ink-naming process. MacLeod and Dunbar (1988)'s shape-color training study showed that, congruency effects in the ink-naming task can be trained by increasing the automaticity of the retrieval process. Automatic retrieval of the associated color was therefore proposed to interfere with the ink-naming process, causing congruency effects in the ink-naming task. Importantly, during MacLeod and Dunbar (1988)'s training, participants were never shown the shapes in their associated colors.

On and on, it seems no past study has successfully managed to train grapheme-color synesthesia in non-synesthete adults. The significant congruency effects found on the ink-naming task post-training, despite being more reliable than the retrieval task (see Chapter 5), could be explained by either orthographic cueing or a temporary better automatization of the retrieval process.

CHAPTER 7. CONCLUSIONS

The three studies presented above aimed to evaluate the extent to which indirect and overt sampling methods have artificially hidden commonalities and differences between synesthetes and non-synesthetes. Participants from the general Danish population have been asked to overtly report their intuitive shape-color associations (Chapter 4; Zelazny et al., 2023) in order to investigate the non-idiosyncratic aspect of the shape-color correspondences. Also, both grapheme-color associator synesthetes and non-synesthetes have been tested in an indirect paradigm, the synesthesia Stroop, to assess the mechanisms at play during the retrieval task (Chapter 5; Zelazny, Liu, & Sørensen, submitted) and to unveil possible confounders that could be involved in its ink-naming task (Chapter 6; Zelazny, Liu, & Sørensen, submitted).

7.1. THE DEGREE OF IDIOSYNCRASY OF SHAPE-COLOR CORRESPONDENCES

Results from our overt report study in the general population (Chapter 4) showed that, while tendencies could be found at the group level for shape-color associations, one-to-one pairings did not occur, questioning whether shape-color correspondences could be viewed as idiosyncratic.

Our investigation (Zelazny et al., 2023) of shape-color associations using a full color wheel for participants to report their instinctive associations allowed to unveil several aspects of this non-idiosyncrasy. First, at the individual shape-level, four of the five shapes tested resulted in at least two significant color associations (e.g., yellow and green for the triangle), showing that at least two associations can co-exist in the population for a given stimulus. Second, comparing between each shape, not all five shapes resulted in the same degree of agreement in the population (e.g., 29% of the participants reported a blue color for the square but only 14% reported yellow associations to the triangle), meaning that the degree of agreement across participants for two given stimuli can vary from simple to double. Third, at the color-level, the range of hues selected differed across shapes, with some shapes being associated to a very specific color (e.g., the square was specifically associated to dark saturated blue) and others to a larger range of a given color (e.g., various types of yellows were associated to the circle ranging from greenish yellow to orangish yellow). Finally, the shape-color associations seem to involve some higher-level mapping, where shape prototypicality appears mapped into colors prototypicality, but each prototypical shape is not just randomly associated to any prototypical color. Instead, shapes are associated to colors following the order of entry into language.

Generally speaking, while significant patterns of color associations appeared for each shape, 63% to 82% of the participants did not agree with the rest of the sample. This means that in fact only a minority of the participants reported the colors significantly associated to each shape (e.g., 29% for the blue square), drawing a picture where shape-color associations are not as universal as originally claimed by Kandinsky (1912).

This could possibly reflect the fact that participants who differed from the group simply reported random colors, meaning that this association only occurs in a portion of the population. Another possibility could be that all participants reported genuine answers, indicating then higher degrees of idiosyncrasy in than previously assumed when testing for associations with a paradigm expecting a one-to-one pairing (e.g., kiki-bouba effect). A final explanation could be that, while all individuals experience every type of cross-modal associations existing, not everyone manages to reliably report all of them, raising the question of what aspect of the cross-modal correspondence makes it easier to overtly report and its degree of consciousness in some individuals.

Overall, enlarging the number of possible answers to a theoretically infinity of colors unveiled that shape-color associations are more varied than originally hypothesized by Kandinsky (1912). Although shape-color associations occur between dimensions of a same modality rather than across modalities, the same tendency could also be present in other correspondences. For example, while most participants showed a tendency to positively map pitch height into lightness, some individuals showed an opposite pattern (Marks, 1974) and the word “bouba” shows a stronger association to a round shape than the word “kiki” to a spiky one (Cwiek et al., 2022). The paradigm presented in Chapter 4 could therefore be repeated to investigate other color associations.

Cross-modal correspondences are mostly studied for auditory and visual pairs, and associations between dimensions of a given modality are greatly understudied (Dreksler & Spence, 2019). Different mechanisms could be involved in different type of cross-modal correspondences (i.e., structural, statistical, linguistic, emotional; (Spence, 2011). If one wants to better evaluate their commonalities and differences with synesthesia, it may therefore be relevant to compare types of correspondences and synesthesia that share various properties. As such, correspondences occurring between dimensions of the visual modality (e.g., shape-color) may be fitting comparison for grapheme-color synesthesia, which also occurs between different dimensions of the visual modality (Marks & Odgaard, 2005). Furthermore, while geometrical shapes and graphemes can be viewed as low-level visual inputs, they also have a higher-lever identity, which could be the ground for the development of color associations.

Finally, according to the Developmental Learning Hypothesis of synesthesia (Watson et al., 2010; 2014; 2017) grapheme-color synesthesia may arise as a neural mechanism for acquiring literacy, where the identity of the concurrent aids in guiding and forming an identity for the inducer. Shape-color association occurring at the conceptual level could indicate that, like grapheme-color synesthesia, shape-color associations help concepts acquisition though color pairing. The Neonatal Hypothesis of synesthesia

(Maurer, 1993; Maurer et al., 2013; Spector & Maurer, 2009) proposes that synesthesia arises from incomplete pruning and failed inhibition of remaining pathways. Cross-modal correspondences are hypothesized to be the manifestation of those leftover pathways being correctly inhibited. Synesthesia originating from concept acquisition would though challenge the link with cross-modal correspondence, as described by Maurer. Nevertheless, cross-modal correspondence reflecting a degree of concept acquisition could reconcile both views, where learning and the conceptual level of the inducers are involved rather than their perceptual one (Chiou & Rich, 2014; Mroczko et al., 2009; Root et al., 2021; Uno et al., 2020; Watson et al., 2010, 2014, 2017) and patterns of associations co-occur between synesthetes and non-synesthetes (e.g., Rich et al., 2005; Simner et al., 2005; Ward, Huckstep, et al., 2006).

7.2. THE DEGREE OF AUTOMATICITY INVOLVED IN THE SYNESTHESIA STROOP

The synesthesia version of the Stroop task has been claimed to be able to indirectly show the presence of synesthetic experiences (Dixon et al., 2000), as well as being able to differentiate between synesthetes who experience their color internally and those who experience them externally (Dixon et al., 2004). In Zelazny, Liu, & Sørensen (submitted; Chapter 5) our results showed several elements that question these claims.

First, the retrieval task of the synesthesia Stroop appears unable to differentiate between synesthetic and simply memorized non-synesthetic letter-color associations. Congruency effects in the retrieval task therefore relies on processes that do not necessarily involve a synesthetic experience.
Our results showed that, the more difficult the retrieval process, the larger the congruency effect on the retrieval task. When synesthetes had to both ignore their synesthetic colors and retrieve memorized associations the congruency effect was the largest (128ms), followed by non-synesthetes controls who only had to retrieve memorized associations (119ms) and finally synesthetes who had to retrieve their genuine synesthetic associations (81ms).

Second, our group of associator synesthetes did not show the pattern of performances in the synesthesia Stroop previously proposed for internal experiences (Dixon et al., 2004). In fact, they showed the pattern previously attributed to projector synesthetes (larger congruency effects in the ink-naming than retrieval task), and it was the memorized associations instead that produced patterns attributed to associators (larger congruency effects in the retrieval than ink-naming task) by Dixon and colleagues (2004). While it took participants five hours of training the retrieval process to start showing a congruency effect in both the ink-naming and retrieval tasks in MacLeod and Dunbar (1988)'s training study, associator synesthetes can do so for their genuine associations without training their retrieval process (Chapter 5 – Experiment 1).

Overall, congruency effects on the synesthesia Stroop may be due to degrees of automatization of the retrieval process compared to the ink-naming one, rather than the degree of automatization of the synesthetic experience itself, as proposed by Dixon and colleagues (2004). Synesthetes seem therefore to show a degree of automatic retrieval of their genuine association that would take non-synesthetes several hours of training to archive.

Our study did not include a group of projector synesthetes, for this reason, it is possible that projectors still behave differently than associators on the synesthesia Stroop tasks. However, our results, as well as previous studies (Hancock, 2006; Mattingley et al., 2001; Mattingley & Rich, 2004; Nikolić et al., 2007; Rothen, Tsakanikos, et al., 2013), indicate that associator synesthetes show congruency effects in the ink-naming task, and that this congruency effect is larger in the ink-naming than retrieval task. In other words, the performances in the synesthesia Stroop from associators and projectors may not be opposite, casting doubt on whether this phenomenological reports of synesthetes can be found using indirect measures. This is of importance, as studies have since then investigated whether associator and projector synesthetes show different neural activity and brain structures (e.g., Rouw & Scholte, 2007, 2010; van Leeuwen et al., 2011) based on the observation that behavioral differences existed.

Overall, our results showed that both the presence and the magnitude of a congruency effect in the retrieval task does not reflect the presence of a synesthetic experience. Instead, it seems to reflect the non-automatization of the retrieval process and can even be increased as the retrieval process becomes even more difficult and does not tap test synesthetic associations anymore. Critically, other indirect methods requiring color naming may have taken for granted that they tap into the automatic aspect of the synesthetic experience, rather than into the automaticity with which the name of the synesthetic color is retrieved. Namely, priming tasks that require naming the color of a target following a synesthetic inducer (Dixon et al., 2000; Gebuis et al., 2009b, 2009a; Mattingley et al., 2001; Spruyt et al., 2009) could produce congruent effects due an automatic retrieval of the synesthetic color name of the prime, which then interferes with the color of the target to be named. Interestingly, Gebuis and colleagues (2009a) failed to find a difference between projector and associator synesthetes in such a priming task, indicating that whether the task taps into the automatic synesthetic process or the automatic retrieval of the synesthetic color name, the degree of automaticity might be the same whether the synesthetic color is experienced internally or externally, further challenging Dixon and colleagues (2004)'s claim.

As previously stated, the associator synesthetes showed a degree of automatization of the retrieval process quite extraordinary compared to non-synesthetes. The fact that the automaticity could be placed at the level of the retrieval process rather than at the level of the synesthetic color experience itself has implications regarding theories of the origin of synesthesia. Dixon and colleagues (2004) proposed that in projectors larger congruency effects in the ink-naming than retrieval task could reflect processes involved in the synesthetic color experience being more automatic than the ones involved in the stimuli color experience. Such an interpretation echoes to studies that tried to evaluate whether synesthetic color experiences were similar to real color experiences. As presented in section 3.2.1.1 the pop-out effect originally found in the visual search task appears very difficult to replicate. Also, neuroimaging studies have struggled to find consistent activation in color areas, as shown in section 2.3.1.

A retrieval process as automatized as the ink-naming one could instead support the involvement of the conceptual level of the color information in the synesthetic color experience (Chiou & Rich, 2014). MacLeod & Dunbar (1988) did not involve any color information during the training, only color terms, meaning that participants could have formed associations at the conceptual level of the color information. The acquisition of color terms in childhood indeed depends on the formation of an abstract color representation (Kowalski & Zimiles, 2006).

It is nevertheless unsure which brain area would reflect this automatized retrieval process. Larger activity in the left dorsolateral prefrontal cortex was associated to implementing more cognitive control during the ink-naming than word reading tasks in a standard Stroop task (Kerns et al., 2004; MacDonald et al., 2000). However, Chiou & Rich (2014) proposed that the conceptual level of the synesthetic color concurrent could be located at the level of the anterior temporal lobe. Furthermore, transcranial magnetic stimulation at the level of the right parietal lobe cancelled the interference on the ink-naming synesthesia Stroop (Esterman et al., 2006). The automatized retrieval process may therefore involve a several processes, involving conceptual color representation at the level of the anterior temporal lobe, attentional binding at the seat of the parietal lobe, maintaining the attentional demands from the task at the level of the left dorsolateral prefrontal cortex, and conflict monitoring at the level of the anterior cingulate cortex (van der Veen et al., 2014; MacDonald et al., 2000).

7.3. ORTHOGRAPHIC CUEING

The synesthesia Stroop has been used as a recurring method to indirectly evaluate the success of attempts to train grapheme-color synesthesia in non-synesthete adults (e.g., Bor et al., 2014; Colizoli et al., 2012; Meier & Rothen, 2009). However, while training studies have focused on letter-color associations, the original synesthesia Stroop studies in synesthetes used digit stimuli (Dixon et al., 2000, 2004). In Zelazny, Lui, & Sørensen (submitted; Chapter 6) the results showed that training letter-color associations should come with a careful selection of letter stimuli, as resulting congruency effects can be confounded by reading processes.

Our results from Chapter 5 showed that the ink-naming task is much more reliable at detecting the presence of a genuine synesthetic experience than the retrieval one. However, we found that if stimuli are not carefully selected, a congruency effect can occur in the ink-naming task in the absence of any synesthetic experience. Namely, orthographic cueing (e.g., “R” cues the word “red”) can produce a congruency effect

in the ink-naming task.
This is of importance as, first of all, the most extensive training study to date, and only study to claim that the congruency effect remained in the ink-naming task three months after training, found a congruency effect that was potentially only due to orthographic cueing (Bor et al., 2014). Second, grapheme-color synesthetes commonly report associations based on the initial letter of a color word (Rich et al., 2005; Simner et al., 2005). As such, running a synesthesia Stroop on those letters would not be able to assess reliably the synesthetic experience, and should therefore be avoided.

The synesthesia Stroop ink-naming task has though found congruency effects post-training for non-orthographic pairings (Colizoli et al., 2012; Meier & Rothen, 2009). However, MacLeod and Dunbar (1988) also showed that congruent effects in the ink-naming task could be due to the retrieval process itself being trained to becoming more automatized than the ink-naming one, relying though on processes independent from the synesthetic ones. In the absence of perceptual experiences post-training but in the presence of a congruency effect in an ink-naming task (Meier & Rothen, 2009), this automaticity reversal process casts doubt on whether the synesthesia Stroop is a fitting task to attest whether non-synesthetes have been trained to acquire synesthesia altogether.

7.4. GENERAL CONCLUSION

While undeniably developmental synesthetes report sensory experiences of a concurrent that do not occur in the rest of the population (Grossenbacher & Lovelace, 2001; Simner, 2012; Ward, 2013), current sampling methods can artificially diminish the commonalities between rare synesthetic experiences and common cross-modal correspondence, and at the same time, overlooked the specificity of performances from synesthetes.
Namely, while an overt report method has been designed (Eagleman et al., 2007) to allow synesthetes to freely report their experience from a theoretical infinity of color options, many studies investigating color-related cross-modal correspondences only allow participants to report associations from a restricted pre-selected number of colors (Albertazzi et al., 2013; Chen, Tanaka, Matsuyoshi, et al., 2015, 2016; Chen, Tanaka, Namatame, et al., 2015; Dadam et al., 2012; de Valk et al., 2017; Dreksler & Spence, 2019; Griscom, 2015; Kim, 2013; Levitan et al., 2014; Lin et al., 2021; Malfatti et al., 2014; Maric & Jacquot, 2013; Nehmé et al., 2016; Palmer et al., 2013; Palmer & Schloss, 2010; Ren et al., 2012; Schloss et al., 2020; Shin et al., 2020; Wright et al., 2017; Xiuwen et al., 2018). In comparison, those allowing participants to freely choose their answers from an amount of colors similar to what is offered to synesthetes are still a minority (Delazio et al., 2017; Lindborg, 2014; Lindborg & Friberg, 2015; Ludwig & Simner, 2013; Saluja & Stevenson, 2018; Slobodenyuk et al., 2015; Wang & Li, 2022).
This methodological difference may have caused reports of color-related cross-modal

correspondences to artificially appear more universal than in reality.
We found that when allowing participants to report their shape-color associations from a full color wheel one-to-one pairings were not the rule and some degrees of idiosyncrasy seem to appear, questioning whether cross-modal correspondences are truly less idiosyncratic than synesthetic associations.
Furthermore, our results showed that associations could occur at the conceptual level in cross-modal correspondence, as previously hypothesized for synesthesia. Such a possibility could open the way for other ways in which cross-modal correspondences are related, apart from testifying of leftover connections between brain areas (Maurer, 1993; Maurer et al., 2013; Spector & Maurer, 2009).

Nevertheless, directly assuming that similar performances in synesthetes and non-synesthetes reveal similar mechanisms may have artificially lessened the differences between the two groups. More specifically, congruency effects in the synesthesia Stroop seem to be able to occur in the absence of a synesthetic experience, both for the retrieval and ink-naming tasks. Indeed, training the retrieval process and making use of orthographic cueing are enough to cause congruency effects in non-synesthetes in the ink-naming task, while the natural non-automatic aspect retrieval process causes congruency effects in the retrieval task in the absence of synesthetic experiences. This has important consequences for our possibility to evaluate whether synesthesia can be trained in non-synesthetes, but also and mainly to fully understand the underlying mechanisms of synesthesia. Indeed, the ink-naming and retrieval tasks of the synesthesia Stroop, may not provide behavioral evidence for phenomenological differences regarding the internal (associator) and external (projector) synesthetic experiences.

Bringing together the results from the studies presented in this thesis, the study presented in Chapter 4 showed that some, if not all, individuals can overtly report their shape-color correspondences. It would be interesting in the future to run an ink-naming and retrieval Stroop task on the shape-color associations of synesthetes (such as those shown in Fig. 2-1 for two synesthetes; Zelazny & Sørensen, 2022) and non-synesthetes (tapping into their idiosyncratic cross-modal correspondence) in order to evaluate the automatization of the retrieval process for intuitive associations, as MacLeod and Dunbar (1988) used shape-color pairs they had predefined themselves.

In conclusion, methods to assess color associations are valuable tools to establish the various types of associations existing, the patterns of associations, and to also understand their underlying mechanisms. Nevertheless, decisions made while designing the various tasks can also greatly influence the outcome results. Focus needs therefore to be put on understanding the mechanisms and possible confounders that can produce those various outcome results, rather than attesting their mere presence.

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