Summary
Synesthesia: The Comprehensive Examination of Behavioural and Developmental Perspective

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It is accepted that there are factors that make some people more creative than others such as German opera composer and performer Richard Wagner (1813-1883), Dutch painter Vincent Van Gogh (1853-1890), Russian writer Vladimir Nabokov (1899-1977), and American physicist Richard Feynman (1918-1988). When we take a closer look at these artists, it can be seen that a prominent common feature of all these names is synesthesia (Ione, 2009 & Simner, 2019, p. 75).

Synesthesia can be defined as a perceptual condition where a stimulation occurring either in one sensory or cognitive modality causes involuntary experiences in another modality, and it affects 4.4% of the general population (Sagiv, 2005; Simner, 2019, p.27; Simner et al., 2006; Harvey, 2013). It literally means "*merge of the senses*" (Cytowic and Eagleman, 2009, p.1; Cytowic, 2002, p.33), it is formed as the combination of the Greek words *syn* = together and + *aisthaesis* = perception (Cytowic and Eagleman, 2009, p.2). The well-known synesthesia researcher Julia Simner explains the term synesthesia in her book (Simner, 2019) indicated as:

"*Synesthesia provides us intriguing insights about how the human mind perceives reality, referring not only to temporary information from the outside of the world but also to the permanent reformation of this information as it enters the brain. To comprehend this perception, we need to understand that the brain is not just a passive device that observes the world. Constantly, every human brain regulates signals that come from the environment in certain ways. Synesthesia is a condition that occurs when this organization is differentiated (p.28). Those with synesthesia rarely see this as an obstacle; Therefore, studying synesthesia aims to better understand the brain, not to find a cure* (Harvey, 2013)."

Synesthesia leads to perceptible-sensory experiences, and it can occur in different ways simultaneously (Grossenbacher & Lovelace, 2001). This means that there are different types of synesthesia. In these concurrents, while the term stimulus (*inducer*) is used to describe the stimulus that triggers the synesthetic experience, the term *concurrent* is used to indicate the synesthetic experience that occurs in the modality where synesthesia occurs (Ward & Simner, 2003; Simner, 2018). People experiencing at least one of these perceptual states are called "*synesthetes*. As an example, while listening to music, a synesthete may also experience a physical sense of touch (e.g., sound-touch synesthesia). Besides, while reading a book, they can perceive letters in different colors (grapheme-color synesthesia) (Ward and Simner, 2020; Cytowic and Eagleman, 2009, p.34).

Synesthesia shows that more than one sensory modality plays a role in the formation of perceptual experiences, and it is known to affect the processes of imagery, memory, and particularly perception (Safran & Sanda, 2015). As it seems, understanding the mechanism of synesthesia can provide important clues to explain the mechanisms of information processing and normal perceptual development. This situation, on the one hand, makes synesthesia a difficult subject to be studied experimentally, but on the other, it is a necessary subject. Although the normal sensory perception process and synesthetic experiences are similar, they differ from each other in many aspects. For instance, certain forms of visual imagery and imaginary memory distinguish synesthesia from other perceptual phenomena. Together with synesthesia studies, how and where different sensory modalities interact in the brain, and how the elements encoded by different brain areas are combined to produce perception, decision, and action (Feldman, 2008). 2013) and how sensory perception develops can be better understood.

The Development of Synesthesia and Various Hypotheses

Today, there are many theories explaining how synesthetic concurrents are formed and how a synesthete maintains this feature during development, and the differences between non-synesthetes and synesthetes in the etiology of synesthesia. These include Neonatal synesthesia, Hyperconnectivity, Disinhibition-unmasking hypothesis, Learned association, and Awareness theories (Meier, 2021). Within these theoretical approaches, in this article, we focused to discuss The Neonatal Synaesthesia Hypothesis, which is still widely supported today and was proposed in 1988 by Mauer, D and Mauer, C.

Neonatal Synesthesia Hypothesis

The main assumption of the theory is that all people are born as synesthetes and most of them lose this ability during development and develop as non-synesthetic adults. However, somehow some of them keep this ability and become adult synesthetes (Ward & Simner, 2020). It is thought that the model explains the hereditary transmission in synesthetic simultaneous experiences (Baron Cohen, 1996), neurobiological and developmental differences between synesthetes and non-synesthetes (Maurer and Mondloch., 2006). The propositions that provide evidence for the theory come from several unique observations:

1. **More synaptic connections in infants**.Synaptic density is the highest immediately after birth, and this, in sensory cortical regions, decrases to adult levels at an earlier stage compared to other regions (Huttenlocher and Dabholkar, 1997).
2. **Less specialized area in the brain during infancy**. In infancy, cortical regions are much less specialized and, in particular, they may respond more strongly to multi-sensory brain areas than children or adults. To illustrate, regions normally specialized in producing speech respond more strongly to visual stimuli early in life (Tzourio-Mazoyer et al., 2002).
3. **Synesthesia-like tendencies in early life.** In the study conducted by Walker et al. (2010), 3-4-month-old babies tended towards high and pointed shapes when played in a high tone, and towards low and rounded shapes when played in a low tone.

This article aims to explain the relationship between synesthesia and behavioral learning by examining the neurobiological and genetic implications on the basis of the neonatal hypothesis. Within this scope, firstly the phenomenon of synesthesia, its development, and different theories about it was explained. After that, since these theories were developed from the neonatal synesthesia hypothesis, the neurobiological and genetic consequences of synesthesia was mentioned in the context of this hypothesis. Finally, the interaction between synesthesia and the learning process was examined in detail. Analyzing the literature, even though there are many factors that affect cognitive processes, especially perception (Hsu and Bai, 2022; Kim, and Jeong- Mo Park., 2017), the phenomenon of synesthesia is not among these factors yet. In this respect, this article points to close the gap in the literature and is the first written about the phenomenon of synesthesia at the national level.

Method

The articles included in the review were searched in Web of Science, Science Direct, PsychInfo, PsycArticles Google Scholar databases using the keywords "synaesthesia", genetics, neurobiology/neuroimaging, learning/behavioral learning, adaptation, neonatal hypothesis and the word synesthesia. Relevant publications consist of review and research articles published in the last 25 years. Since no current meta-analysis study was found in the field, meta-analysis studies were excluded on the grounds that they were insufficient. The articles included in the study were classified according to subheadings. According to this; A total of 52 articles were included in the study, including 9 articles examining neonatal synesthesia, 8 articles explaining general synesthesia theories, 5 articles on learning, 10 articles based on genetics, and 20 articles examining the foundations of synesthesia-neurobiology. In addition, 7 books, 1 opinion article, and 1 research report with publication dates ranging from 2002-2019 were also included in the study.

Results

Neurobiological Evidence and Implications

The Neonatal Synesthesia Hypothesis is interesting in many ways as it attempts to interpret brain development by presenting a wide range of data (Ward and Simner, 2020). A large number of experimental studies have shown that the primitive cortex is less specialized in newborns than in adults. For example, in the study of Sur and Leamey (2001) with baby ferrets, when retinal axons were reconnected to the auditory cortex, the auditory cortex developed not with tonotopic stripes as usual, but as cylindrical gear wheels seen in the visual cortex, and later the neurons in the auditory cortex became sensitive to visual stimuli. These experiments showing the emergence of normal silent stimuli (from visual stimulus to auditory stimulus) can also be seen in newborns and may be an underlying mechanism of synesthesia (Maurer and Mondloch, 2005).

Scientific studies conducted on neurobiological bases benefit from various neuroimaging techniques. In the study of Rouw and Scholte (2007), by using diffusion tensor imaging, a higher amount of white matter was observed in the synesthetes in different regions of the brain compared to the control group. In another study conducted with a different type of synesthesia (Simner, 2019), people with color-touch synesthesia aged 5-74 years associated smooth texture with light and vibrant colors. The research draws attention that the relationship between smoothness and color vibrancy was found especially in young subjects, but not in older subjects. The results are captivating as they show that synesthetic associations, which are high in newborn individuals, may decrease as they develop over time, just as tested in the neonatal synesthesia hypothesis.

Genetic Evidence and Implications

Even though many of the hypotheses formulating to explain the genetic basis of synesthesia suggest that each type of synesthesia is associated with a particular gene or gene group, a recent study (Barnett and Newell, 2008) revealed that each type of synesthesia may differentiate in the household. In this study, different types of synesthesia were observed in different members of the same family (first-degree siblings and cousins). In 2010, Julian Asher and his team collected a total of 43 synesthete families who experienced letters, numbers, days of the week, and music with color and hypothesized that these family members could form a similar synesthesia group with the same genetic origin. When DNA samples taken from families were analyzed, results thought to cause synesthesia in certain areas of the genome were determined, and it was seen that synesthesia of families was associated with chromosome 2 located near a region known as 2a24.

Behavioural Evidence and Implications

While the neonatal synesthesia hypothesis supports that synesthesia is innate and genetically inherited (Bor et al., 2014), it also draws attention to whether synesthetic experiences can be learned between individuals from the beginning of birth or as they became adulthood (Ward & Simner, 2020). It is difficult to explain synesthetic experiences in terms of general learning procedures as the characteristics of synesthetic experiences are unique, have a wide range of diversity, and are not based on any clear functional relationship between stimuli (Deroy & Spence, 2013).

There is also a small but growing literature showing that synesthesia can affect learning. For example, synesthetes seem to be able to use their experiences as nymonic responses (a memory technique) and even exploit them as learning new abstract categories. In this context, case studies often highlight the unusual memory abilities of synesthetes. These include synesthetes, who perfectly remember long lists of names for weeks (Millsetal., 2006) and perfectly remind lists of words (Luria, 1968) in a test by asking random words 20 years after initial exposure. In the study of Smilek et al. (2002), synesthete participants also remembered correctly 50-digit numbers after 2-3 months after a few minutes of learning.

Discussion

Without a doubt he phenomenon of synesthesia presents significant findings that will contribute to the fields of epigenetics and neuroscience, especially information processing processes. However, it is a theory discussed from some points today. First, any evidence put forward for the theory is indirect and has not been tested as a whole in sticking studies so far. For example, neuroimaging techniques have not yet been applied to the nascent brains of infant synesthetes. This means that there is no direct evidence as to whether the nerve pathways proposed in theory fail to prune. This may partly due to the fact that it is not yet possible to diagnose synesthesia with available facilities. As a solution, by scanning the brains of infants of adult synesthetes, the neurological development of these infants can be observed longitudinally, with the knowledge that these are infants most likely to emerge as adult synesthetes. Surely, the practical and ethical limitations of such a practice must be considered.

In the genetics field, although it is known that synesthesia is an inherited phenomenon transmitted on the S2a receptor (Brang and Ramachandran, 2008), it is not fully understood in which brain, through which pathways, and how this receptor performs this function. In addition, this gene seems to indicate synesthetic brain development in the individual. Therefore, with genetic studies to be supported in the literature, it should be investigated how the genes that cause synesthesia play a role in the development of the synesthetic brain.

On the other hand, accepting the difficulties of synesthesia in the behavioural learning studies, in a number of educational studies on the learning dimension, there are significant differences between the effects of short-term training in adults and the long-term associations of synesthetes. Although non-synestetic participants reported experiences that seemed very similar to true synesthetes, it was necessary to conclude that the two were qualitatively different. For this reason, longitudinal studies are needed in order to see the change in synesthesia and learning with long-term training and, if possible, in terms of development. In addition mentioned above, it has been observed that synesthesia can affect certain learning styles. For example, studies have shown that synesthetes have certain advantages in terms of perception. It is clear that more research is needed to include new ways of testing synesthetic performance of styles, particularly in perception and memory tasks. As an example, it should be emphasized how the intelligence (IQ) factor changes in synesthesia as Simner et al. (2009) suggested that increased connectivity in white matter pathways in visuospatial synesthesia may be associated with high intelligence level (IQ). Afterwards, Rouw and Scholte (2016) statistically confirmed the increased intelligence score in synesthetes, but stated that this high intelligence was not driven by certain types of synesthesia.

It seems that some studies have shown that overall cognitive performance increases in relation to synesthesia, but the ways in which these cognitive functions are directly related to the presence of synesthesia are relative.

Conclusion

The Neonatal Synesthesia Hypothesis is a holistic theory, but it also has missing dimensions. Here we saw that synesthesia has a possible genetic inheritance. Therefore, we can conclude that synesthesia is not directly caused by postnatally acquired events such as learning, but is likely to be predetermined in some way at birth and epigenetic and environmental factors might have effects on it.

Keywords: Synesthesia, behavioural learning, neonatal synesthesia hypothesis, neurobiology, genetic