A Review of Synesthesia

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Introduction

Can you imagine what it would be like to see a sound, or taste a vision? For people with the rare syndrome of synesthesia, such exotic sensations are part of everyday life. Synesthesia, derived from the Greek words *syn* (union) and *aisthesis* (sensation), is the remarkable experience of cross-sensory perception. Stimulation of one sensory modality consistently causes sensation in one or more other senses. This condition has been known for at least 200 years; famous synesthetes include novelist Vladimir Nobokov and composer Alexander Scriabin. To get a flavor for synesthetic experience, consider the following examples (taken from Cytowic 89):

> What strikes me is the color of someone's voice. [Name] has a crumbly, yellow voice, like a flame with protruding fibers. Sometimes I get so interested in the voice I can't understand what's being said.
>
> Spearmint tastes like cool, glass columns. Lemon is a pointed shape, pressed into my face and hands. It's like laying my hands on a bed of nails.
>
> The name Paul is such an ugly color, it's gray and ugly. I told her, "Name the baby anything but Paul." She couldn't understand why, and I said, "It's such an awful color, that name Paul." She thought I was out of my mind.

For a synesthete, sounds can cause colors or images of shapes to appear, tastes can elicit sensations of touch, or the viewing of words or digits can invoke the perception of specific colors. Furthermore, these experiences come unsolicited, outside the domain of conscious control.

In this review, I will be exploring what is known about this remarkable condition, giving a brief overview of current knowledge and examining recent research in the field. Specifically, this review will focus on a few key questions: What are the types and characteristics of synesthesia? Is synesthesia amenable to scientific research? What is its neurophysiological basis? Is it learned or inherited? Finally, what is our current status in understanding this phenomenon? The goal of this paper is for the reader to emerge with a general introduction to the subject, familiarity with recent synesthesia research, and an overview of current debate over the cause and neural basis of synesthesia.

Why is synesthesia of interest?

In addition to being a fascinating and unsolved rarity of human perception, synesthesia seems to involve many aspects common to all people. It is a potent example of sensory integration that may point the way to the neural mechanisms that process and interrelate our perceptual experience. Multi-sensory processing occurs in normally in humans, including the unified experience of the position of our bodies in space (a combination of vision, touch, and proprioception) and the ability to craft relations between distinct senses, as seen in synesthetic metaphor (Day 1996) or mappings of high and low pitches to light and dark colors (Hubbard 1996). The potential for synesthesia may be present in all people, as drugs such as mescaline and LSD can induce synesthetic experiences. Synesthesia also has the potential to teach us more about perceptual systems in general, including how they operate, how they develop over time, and what neurophysiological structures mediate experience. Furthermore, given synesthesia's striking perceptual experiences, synesthesia research is another avenue that may shed light on the elusive nature of consciousness itself. In sum, synesthesia is of interest for the same reasons that anything else is of interest to cognitive neuroscience – it can lead to a greater understanding of the ties between cognition and biology.

What are the types and characteristics of synesthesia?

Synesthesia comes in a host of different forms. The most common form of synesthesia is hearing induced vision (colored hearing), where sounds or spoken words trigger visual experiences. Other common forms include color perception elicited by the reading of words (based in the spelling or sound of written words) or digits. Synesthesia occurs in a variety of other forms as well, including hearing induced touch, vision induced smell, and others. While synesthesia involving either taste or smell does occur, it tends to be much rarer in practice (Cytowic 1995). An important thing to note is the directed nature of synesthetic mappings – they represent a one-way projection. Therefore, a synesthete who sees colors when hearing spoken words does not then necessarily hear words when viewing colors.

The experience of synesthesia is part of the background of people's lives, present since earliest memories and consistent in its manifestation over the years. Richard Cytowic, a major researcher/writer on synesthesia, outlines the aspects of synesthesia, collected over a number of case studies, crucial to a clinical diagnosis (Cytowic 1995). First, synesthesia is effortless – it is a passive sensation that is elicited by a typically identifiable stimulus. As such, synesthesia can not be consciously controlled any more than other more 'normal' perceptions. Another predominate feature is that synesthesia is projected – it is experienced in external space, usually near the body. Cytowic gives the example of patient DS, who when listening to music sees objects - "falling gold balls, shooting lines, metallic waves like oscilloscope tracings - that float on a 'screen' six inches from her nose." Third, synesthetic experience tends to be stable. For example, if someone experiences the color red when viewing the digit ‘3’, they always experience exactly that color. Experiments to test the consistency of synesthetic experience (Baron-Cohen 1993) found that after a period of one year, 92.3% of reported synesthetic responses were identical with those given a year earlier. Furthermore, synesthetic experiences are generic and unelaborated. Synesthetes may experience colors, simple shapes, or feel rough or smooth textures, and while these may be highly specific, they do not go beyond base perceptions. For example, the experienced image of a detailed landscape or icon would most likely not be part of a true synesthetic experience.

Another characteristic is that synesthesia is idiosyncratic. That is, two synesthetes with the same type of synesthesia will most likely not share the same synesthetic experiences. For example, upon hearing the word ‘demanding’, color word synesthetes will experience different color sensations. Overall, researchers have been unable to find a pattern between different synesthetes, though one study (Baron-Cohen 1993) found that for some graphemic-chromatic (colored letter) synesthetes, the letters ‘i’, ‘o’, and ‘u’ consistently elicited colors in the same range with 88.9% consistency. The letter ‘o’ was particularly striking, eliciting the color white both in this study and in others.

Both Cytowic (Cytowic 1995) and Simon Baron-Cohen (Baron-Cohen 1996) have done extensive research and cataloguing of synesthetes, and have found some interesting demographic results. The first, unsurprisingly, is that synesthesia is very rare. Within the US, Cytowic’s studies estimate that synesthesia occurs in roughly 1 out of every 25,000 people, while in the UK, Baron-Cohen estimates a much more substantial 1 out of 2000. Both researchers have found that most synesthetes are predominantly female (Cytowic finds a ratio of 3:1, Baron-Cohen 6:1). Synesthetes are also more likely to be left-handed. Interestingly, synesthesia appears to run in families, though a case has never been found of a father transferring synesthesia to a son. This leads one to hypothesize that synesthesia is a genetic, X-chromosome linked trait. Additionally, most synesthetes seem to be healthy and bright, performing normally on neurological exams, scoring high on intelligence tests and showing above average memory abilities (possibly related to the cross-sensory perception). Many synesthetes, however, do suffer from mathematical deficiencies.

Is synesthesia amenable to scientific research?

Before proceeding any further it is important to ask if synesthesia lends itself to scientific research. So far the evidence presented rests solely on the self-reports of synesthetes, and while this may be convincing, synesthetic experience has a subjective, first person ontology not directly verifiable by current scientific tools. Similarly, Cytowic's requirements for synesthesia also seem beyond scientific verification, as they largely rely upon personal reports. While some researchers like Cytowic show no qualms carrying out research on subjective data, scientists as a whole are often wary of unobjective or 'unscientific' research. Fortunately, a number of experiments have shown that while direct synesthetic experience may remain out of reach, it carries with it results and neurophysiological correlates that can be directly observed. In addition to studies that provide direct evidence for physiological differences in synesthetes (Paulesu 1995, Schiltz 1999 – to be covered in detail later), recent psychological experimentation shows that synesthesia can be a subject of proper scientific research.

Mills et al (Mills 1999) used a Stroop-style test on participant GS, a synesthete for whom digits trigger color perception, to provide objective evidence for some of the self-reported aspects of synesthesia, namely its automatic and unidirectional nature. In the experiment, GS was presented sequences of digits and colored circles. Some of the digits were colored black, others colored as to match her synesthetic perception, and others colored to mismatch. In a color naming task, GS was presented a colored digit or a circle and asked to name the printed color, unless the stimulus was a black digit, in which case she was instead to report her synesthetically perceived color. In a digit naming task, GS was asked to name what digits she saw when digits were displayed. If a colored circle was displayed, GS was to name the digit whose synesthetic color matched the circle. This experiment was done twice, with a four month lapse between trials. For the second experiment, GS was instructed to keep mismatched colors from interfering with her performance.

The results of the experiment showed that for each condition, color naming took longer than digit naming. In the color naming task, the mismatched condition was significantly slower than the other three conditions, which did not differ significantly from each other. In the digit naming task, GS took significantly longer to name the digit that corresponds to a colored circle than to read a digit under any of the color conditions, which were not significantly different from each other. This is to be expected given the extra cognitive steps required. Another interesting and somewhat surprising result is that GS was actually faster at naming the digit that corresponds to a color circle than naming the color itself.

According to the analysis of Mills et al, these results provide objective evidence for both the automatic and unidirectional properties reported by synesthetes. A likely explanation of GS's performance on the mismatched color naming task is that GS's synesthesia caused her to experience two disparate colors, causing an effect not unlike that in the classic Stroop test, slowing down response times (this despite the fact that GS herself was not consciously aware of any slowing). Coupled with the fact that there was no significant time difference between color namings for matched digits, black digits, and color circles, this implies that, indeed, synesthesia is an automatic process, not mediated by any conscious processing. Furthermore, the near identical naming times for presented digits regardless of color shows no Stroop-type interference effect, and thus is consistent with the idea that synesthetic mappings are unidirectional. Finally, Mills et al attribute the quicker recall of digit names than color names from color circles to a cognitive ability to retrieve digit names faster than color names, and argue that this is consistent with results from classic Stroop studies.

What is the neurophysiological basis of synesthesia?

Of primary interest to cognitive neuroscience is the connection between biology and cognition, and synesthesia is no exception. While I had no trouble locating papers on synesthesia in general, it seemed that there were few scientific experiments concerned with revealing the underlying biological mechanisms of synesthesia. One early imaging study by Cytowic indicates a decrease in cortical activation during synesthesia. There are also a handful of recent studies that use modern neuroimaging and recording tools to explore the neural basis of synesthesia. Below the results of Cytowic's experiment and others using Positron Emission Tomography (PET) and measuring Event-Related Potentials (ERPs) in synesthetes are discussed.

Using the Xenon-133 inhalation technique on a taste-shape synesthete, Cytowic discovered that regional bloodflow, and thus presumably brain activation, actually decreased during synesthetic experience (discussed in Paulesu 1995 and Schiltz 1999). These decreases were widespread throughout the neocortex. This lack of cerebral activation, along with other evidence (including synesthetes' advanced memory), has led Cytowic to postulate that the limbic system is critical for synesthesia. Cytowic singles out the hippocampus as an especially important node in this system, though due to limitations in Xenon-133 imaging, no data from the limbic system was gathered. While an interesting hypothesis, obviously more neurological data is needed to reach a strong conclusion. Cytowic also strongly believes that synesthetic experience is dominated by the left hemisphere, though the evidence for this was not listed in (Cytowic 1995) and I was unable to procure any of his books.

To explore the neurophysiology of synesthetic experience, Paulesu, Baron-Cohen and other colleagues performed a PET experiment to measure brain activation (by measurement of rCBF – regional cerebral blood flow) in color-word synesthetes (Paulesu 1995). Six female participants were prescreened for color-word synesthesia (color perception evoked by spoken words) and no synesthesia for any other auditory stimuli. The synesthetes were compared against an age and handedness matched control group of six women who had never experienced synesthesia. The participants underwent PET scanning under a control task in which single pure tones were delivered through earphones, as well as an experimental task in which spoken words were presented. Participants were blind folded and instructed to tap their left index finger for every tone or word heard.

The resulting PET images show that in both subject groups the spoken word stimuli caused activation in a series of brain areas implicated in language, including the superior and middle temporal gyri bilaterally and the left inferior frontal gyrus. The group with synesthesia showed additional activation in the middle frontal gyrus and the insula on the right, and the posterior inferior temporal (PIT) cortex on the left. There was also activation in the parietal-occipital junctions and a significant decrease in rCBF in the lingual gyrus. Small rCBF increases were also detected in human area V4 and the right PIT cortex, but the rise was too statistically small to deem significant.

These results provide many clues into the mystery of synesthesia. In both humans and monkeys, the PIT cortex has been correlated with complex forms of color perception as well as higher forms of processing such as multimodal visual integration in tasks such as object recognition. Thus activation of the PIT, which lays on the border of language and visual areas, may help explain both the visual / language feature integration and color perception of the subjects. Furthermore, in the macaque monkey it is known that the PIT cortex has a much rougher representation of the visual field than area V4 (which in turn is much less precise than V1). This is consistent with synesthetes' reports that synesthetic perception is not localized within the visual field. Due to previous conflicting studies, Paulesu et al were much more hesitant to interpret the activation of the parietal-occipital junctions, but they note that increasing evidence of a color-sensitive cortical field in the region corroborates their findings. Similarly, Paulesu et al were cautious in their analysis of the blood flow decreases in the lingual gyrus, which may represent parts of V2 or V3, due to a current lack of evidence for the biological meaning of regional deactivation. It is interesting to note, however, the lack of activation in primary visual areas during synesthetic experience, implying that conscious visual experience can occur without the activation of V1. Overall, Paulesu et al conclude that activation in the PIT cortex is a likely neurophysiological correlate of synesthetic experience, representing the integration of visual and linguistic features. They suggest that this indicates unusual anatomic connectivity between language and visual areas, and postulate that synesthesia is more likely to occur when two sensory regions share a neurological border, and thus have a greater anatomical chance for integration.

Another, more recent study was done by Schiltz et al, who used electrophysiological recordings to find Event-Related Potentials (ERPs) correlated with synesthetic experience (Schiltz 1999). EEG scalp recordings were taken from 17 graphemic-chromatic synesthetes (synesthetes for whom written letters elicit color perception) and a matched control group while performing a character selection task. White letters from the set { A, E, I, O, U, M } were presented on a black screen, with one of the letters designated as the the 'target'. As the letters were shown in sequences, the participants were to press a button in their right hand when the target letter appeared. This experiment was also repeated using digits from the set { 1, 4, 5, 18 } instead of letters.

In both groups, the resulting ERPs showed a large P300 component (a large positive spike about 300ms after stimulus onset) over parietal regions for target stimuli as compared to non-targets. Over frontal and central areas, however, the synesthetic group showed waveforms with a significantly more positive voltage than controls, both in target and nontarget conditions and over both the letter and digit tasks. Schiltz et al conclude that this positivity most likely indicates cortical inhibition in frontal and pre-frontal structures. This is consistent with Cytowic's finding of decreased cerebral blood flow. Schiltz et al posit that due to the role of the frontal lobe in attentional selection, the inhibition may indicate "an increased distractibility, and possible leakage between the [sensory] modalities." Alternatively, they claim, it could be that frontal regions are richly endowed with multi-sensory neurons and this is the region where synesthesia occurs. Frontal inhibition then may be a regulatory mechanism to keep synesthesia to a minimum, so as to reduce sensory interference.

After analyzing the different studies, no strong consensus about the underpinnings of synesthesia arises. Cytowic claims that the limbic system is central to the phenomena, yet PET imaging showed no additional activation in this region. Paulesu et al found important activation in the PIT cortex in the left hemisphere in synesthesia, weakly supporting Cytowic's claim that the left hemisphere is solely responsible for synesthesia, though other activations were found by Paulesu et al in the right hemisphere. While this is inconsistent with Cytowic's reports of blood flow decrease across the entire cortex, some cerebral blood flow decrease was found in all studies. Cytowic reported it throughout the cortex, Paulesu et al in the lingual gyrus, and Schiltz et al in the frontal lobes. While Cytowic uses the decreased blood flow as evidence of limbic involvement, Schiltz et al actually hypothesize that this decrease may signify the synesthesia itself! Interesting features of these studies which seem to me to invite more explanation are (1) the role of decreased blood flow in synesthesia, and (2) the role of the PIT cortex in color-word synesthetes.

Is synesthesia learned or inherited?

Another important question is whether synesthesia is acquired or innate. Studies presented earlier (Cytowic 1995, Baron-Cohen 1996) provide strong evidence for a genetic component to synesthesia, as both researchers have documented numerous families of synesthetes. Yet this doesn't completely answer the question. Many synesthetes see colors when they view digits or letters, but have no other synesthetic responses. Since number and letter systems must be learned, it is perplexing that these people would develop the very specific synesthesias they have.

One possible explanation is that synesthesia requires certain underlying neural conditions (e.g. cross-sensory connections), which then allow for the later development of synesthesia. Could it then be the case that synesthesia may or may not develop? Interestingly, would the languages or number systems learned influence this development? Another possibility is that the neural mechanisms underlying the synesthesia are very specific, for example a cross modal-connection between a language area responsible for symbol processing and a visual area, and that this predetermines synesthetic experience provided sufficient linguistic development.

In an interesting experiment, Stevenson, Boakes, and Prescott found that they could induce a learned smell-taste synesthesia (Stevenson 1998). By mixing an odor-producing flavorant with sugar, and then letting participants taste the mixture, the researchers found that they could affect the perceived sweetness of the odor. This is significant, they claim, because the nose does not seem to contain any sweetness receptors, unlike the mouth. Thus the experience of sweetness experienced simultaneously with the odor is an example of smell-taste synesthesia. Furthermore, the experiment shows, by changing the perceived sweetness, that this synesthesia can be learned.

While this experiment shows some evidence for learned synesthesia, it is far from convincing. Was there a smell-taste synesthesia present before the experiment? A more convincing study would be if a previously unsweet odor could be made to elicit a sweetness response or vice-versa. It is also well known that taste and smell are already highly integrated senses (in fact, what we commonly think of as taste is a combination of taste, smell, and texture), and this may play a role in the results. If a learned synesthesia between more disparate senses (such as hearing and vision) were demonstrated, this would certainly make waves. Furthermore, given the evidence for a genetic component to synesthesia, learned synesthesias would need to be reconciled against this known pattern. At this point in time it is probably safe to conclude that synesthesia is an inherited trait, but that learning may affect its occurrence.

Current theories of synesthesia

A number of diverse theories on the origins of synesthesia abound. Cytowic gives an overview of numerous theories (Cytowic 82), ranging from a view of synesthesia as undifferentiated neuronal activity to the idea that synesthesia is mediated by higher level processes (i.e. not a result of direct linkage between senses). These theories are given a good treatment by Cytowic, and so I won’t discuss them here, instead focusing on more recent theories. Cytowic’s current theory of synesthesia is that it is part of a normal perceptual process that in synesthetes is made accessible to consciousness prematurely (Cytowic 1995). He entertains the idea that perception is a holistic process, and thus other perceptual modalities get to ‘sample’ an event. Cytowic hypothesizes that normally the interference from other senses is eliminated before the actual percept becomes conscious. In synesthetes, then, this mixing of the senses is made conscious before the differentiation is done. Cytowic’s certainty of the role of the limbic system in synesthesia, as well as the documented decrease in cerebral blood flow, also leads him to uphold the primacy of the limbic system, and thus of emotion, over more cortical, or rational, processes in human dealings. This seems quite a leap to make, especially given the uncertainty involving synesthesia’s true causes, but it is interesting nonetheless.

A different theory is discussed by Baron-Cohen, who believes that synesthesia results from a breakdown in the modularity of perception (Baron-Cohen 1996 #2). Baron-Cohen espouses the theory of neonatal synesthesia, which holds that up until about 4 months of age, infants experience sensory stimuli in an undifferentiated way – e.g. sounds result in auditory, visual, and tactile sensations. Under normal development the senses later differentiate and sensory processing becomes modularized. Synesthesia occurs when this differentiation is incomplete, leaving cross-modal associations between two or more senses. These associations could be the result of lingering neural connections not present in normal subjects, or an unusual lack of inhibition in multi-sensory regions. Baron-Cohen cites as preliminary evidence the Cross-Modal Transfer (CMT) hypothesis, which posits that infants can recognize objects in more than one modality due to an ability to represent objects in an abstract form. Baron-Cohen notes that there is considerable evidence for the CMT theory, which supports the notion of gradual sensory differentiation. It is also noted that transient cross-sensory connections have been found in other species, such as hamsters and cats.

Given our current state of knowledge, there are still many possible explanations for synesthesia, many of them contradictory. Do the varied forms of synesthetic experience all share a common cause, mediated by the limbic system as Cytowic believes, or is each different case unique, the result of direct connections between different sensory processing regions of the brain? The study of Paulesu et al indicates that color-word synesthesia may be tied to cross modal connections in the PIT cortex. The work of other researchers shows there are more cross-sensory association areas to possibly add into the mix. Luciano da Costa notes that researchers have discovered portions of the anterior ectosylvian cortex in cats, a visual processing region, that become sensitive to auditory and tactile stimuli in response to visual deprivation (da Costa 1996). In another paper, Stein et al discuss brain regions capable of multi-sensory processing, specifically the superior colliculus, which develops inter-sensory connections in humans about twelve days after birth (Stein 2000). These findings open up even further possibilities. It is obvious that much more empirical data is needed to confidently state a fundamental theory of synesthesia.

Conclusion

The future of synesthesia research can proceed in a number of ways. Though the phenomenology of synesthesia is now well understood, due largely in part to the work of Cytowic, Baron-Cohen, and the researchers who preceded them, we are just beginning to understand the neural mechanisms that under lie the phenomena. I see a host of possibilities for future research. First, it is important that synesthetes be continually sought out, and their experiences recorded, refining the data collected so far and perhaps adding new twists and turns into the mix. I also think it useful to observe the development of the children of synesthetes (which I believe Baron-

Cohen is now, or at least was recently, doing). This might give us more clues into both the origin of synesthesia (provided the children turn out to be synesthetic) as well as the development of perceptual systems in general. It would also be interesting to see an experiment where Transcranial Magnetic Stimulation (TMS) is performed over the left PIT cortex of color-word synesthetes during spoken word trials. I would expect to see an effect on synesthetic experience, namely a remarkable decline in the sensation. If normal color perception is not affected too aversely (and thus suggests we are interfering with color perception as a whole and not just synesthesia), this would be functional evidence of the role of the PIT cortex in color-word synesthesia. Further imaging and recording studies are called for as well, especially using the more powerful fMRI techniques now available. In addition to finding the activated and deactivated brain regions, I think imaging and recording studies of a number of different types of synesthetes might prove useful in determining if different forms of synesthetic experience share a common feature or if they result from independent causes. Furthermore, it would be useful to compare imaging results against ongoing research on multi-sensory brain regions (like the work discussed in da Costa 1996 and Stein 2000) and look for any interesting correlations. Hopefully as research proceeds, the mysteries of synesthesia will be unraveled.

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