Proceedings of the 12th International Conference on Music Perception and Cognition and the 8th Triennial Conference of the European Society for the Cognitive Sciences of Music, July 23-28, 2012, Thessaloniki, Greece
Cambouropoulos E., Tsougras C., Mavromatis P., Pastiadis K. (Editors)

The Role of Pitch and Timbre in the Synaesthetic Experience

Konstantina Orlandatou

Institute of Musicology, University of Hamburg, Germany
konstantina.orlandatou@hfmt-hamburg.de

ABSTRACT

Synaesthesia is a condition, an involuntary process which occurs, when a stimulus not only stimulates the appropriate sense, but also stimulates another modality at the same time. In order to examine if pitch and timbre influence the synaesthetic visual experience, induced by sound, an experiment with sound-colour synaesthetes (N=22) was conducted. It was found that a) high pitched sounds conclude to a presence of hue, b) low pitched sounds to an absence of hue, c) single frequencies cause a uni-colour sensation and d) multiple high pitched frequencies induce a multi-colour sensation. Variation of chromatic colour, which is present in the sensation, depends on the timbre of the sound. These findings suggest that the synaesthetic mechanism (in case of sound-colour synaesthesia) maps sound to visual sensations depending on the mechanisms underlying temporal and spectral auditory processing.

I. INTRODUCTION

By the phenomenon of synaesthesia, interactions between different modalities occur. For example a sound or a smell can trigger a visual sensation or a pain can be sensed with a specific taste. These interactions can occur between all modalities. The mechanism responsible for synaesthesia is still not known, something that is understandable since there are numerous types of synaesthesia. From the beginning of the 20th century to nowadays, two are the main directions of research: research focusing on interactions between cross-modal associations and research focusing on the neurological causes of this condition. The last 10 years research focuses exclusively on grapheme-colour synaesthesia, in which visual information elicits a sensation of the same modality (visual-to-visual).

A. Neurological mechanisms underlying synaesthesia

Our brain processes sensory information in a hierarchical manner. Sensory processes are separated from low and middle ordered, which are multimodal networked in a higher level. It seems that by synaesthetic experience the neuronal communication occurs on different levels. Every time when we hear a sound, a neuronal activity takes place. It is possible that the induced sound activates neurons of the visual pathway through a cross-talk circuit (Grossenbacher, 1997), which triggers a synaesthetic experience. Cross-modal neural connections are likely to occur between nearby regions as separated cortical areas. Feedback theory assumes that afferent neural signals, transmitted from one level to the next higher level of the sensory pathway, are requited by efferent signals of reverse direction (Cynader et al, 1988).

Synaesthesia has been also considered to be a primitive form of perception ("Ursynästhesie", Wellek, 1929). The hypothesis, that all siblings do not differentiate the input of different senses and therefore are synaesthetes, is based on this theory (Maurer, 1993). From the fourth month cortical maturation allows sensory differentiation and that would explain why most of people lose this ability (synaesthetic pruning).

The limbic system can also play an important role, especially the hippocampus and the hypothalamus, since people experience synaesthesia during epileptic seizures or under use of drugs (Cytowic, 1989). By cross activation theory (Ramachandran & Hubbard, 2001), cortical language systems as well as regions of the visual cortex are involved in grapheme-colour synaesthesia. Comprehension of spoken language and colour-vision are commonly processed. The location and the intensity of activation determine if a person has a low or a high degree of synaesthesia.

It is also supported that synaesthesia is an inherited trait. There is a biological disposition that runs through families and is more common in women rather than in men (Baron-Cohen et al., 1996).

B. Cross-modal associations

By the end of the 19th Century many terms had been used to describe phenomena of audio-visual perception and sound-colour assignments, such as: synopsis, audition colorée, phonisms or photisms, intermodal analogies or intermodal qualities. Sensory qualities, such as intensity, brightness, size, density and roughness are similar for all the sensory areas and are being used to describe properties of a specific modality (Werner, 1966). We know that brightness and sound intensity (bright-loud, dark – low, Argelander, 1927) as well as pitch and brightness (bright photisms – high tones, dark photisms – low tones, Bleuler & Lehmann, 1881) are the most common sensory attributes. But it is not important if someone is synaesthete or not. In both cases, the correlations between the dimensions of visual and auditory experiences are nearly identical. Pitch changes the brightness and the size of the photism and the loudness of a sound can change the brightness of the photism (Marks, 1975). The only difference between cross-modal associations and genuine synaesthetic experience is that synaesthesia occurs involuntary and its appearance can not be consciously controlled. These sensory qualities have been also named as intermodal analogies (Behne, 1991). The person reacts to a stimulus and attempts simultaneously to assign a modality to another, but that happens only if the person is asked to do so and not involuntary, which is a cognitive process. Synaesthesia is high memorable and consistent (since childhood, Cytowic, 1993) whereas intermodal analogies are memorable for approximately one week.

Sound-colour synaesthesia is being evoked from concrete and not randomly associations between the two modalities and the size of visual representation can vary from sound to sound. Low pitched sounds evoke large representations, whereas high pitched sound evokes small representations (Riggs & Karwoski, 1934).

C. Attributes of visual synaesthetic sensation

It can be that multiple mechanisms are responsible for synaesthetic perception. Sound-induced synaesthetic experience consists of different elements. In case of sound-colour synaesthesia, the visual representation of the experience is exactly as complex as sound itself. As sound, which has different spectral and temporal characteristics, such as frequency, amplitude, synaesthetic experience has also different attributes, referring mostly to colour.

In this paper it will be examined how the timbre and the pitch of the sound can affect three main attributes of the experience, in case of sound-colour genuine synaesthesia: chroma (hue), colour plurality and colour brightness and how the synaesthetic mechanism maps these attributes based on sound characteristics.

Chroma (not to be confused with the measure of colour purity in the Munsell colour system) describes if hue (main colour attribute) is present during the synaesthetic experience. Presence or absence of hue determines if the colours are chromatic or achromatic. Achromatic colours are colours without hue and these are white, black and grey. Colours with hue are called chromatic, such as primary colours red, green and blue.

Colour plurality is another attribute of the experience, which describes if the visual representation consists of one or more that one colours. If the sound evokes one colour the experience is uni-colour, if the sound evokes more than one colours at a time, then the experience is multi-colour.

Colour brightness describes if the colours, perceived during the experience, are dark or bright. Brightness can be measured from different colour systems, such as the National Colour System (NCS) or the Munsell colour system. We are living in a world dominated by media. The colour system, which is most commonly nowadays used in graphic design, internet, computer, TV and other media, is the RGB model system. The separation between bright and dark colours, in this study, is based on this model. The RGB colour model shows the proportions of the 3 primary colours (R = red, G = green, B = blue) needed, in order to create a new colour. The final colour is created by adding the proportions of these colours. Black has an RGB value of 0, 0, 0 (contains no other colour) and white has an RGB value of 255, 255, 255 (contains all colours). That means, the more the RGB values tend to 0, the darkest the colour is, as shown in the table below.

Table 1. RGB values of 10 main colours.

Colour	R	G	B	description
Black	0	0	0	dark
Blue	0	0	255	dark
Green	0	255	0	dark
Red	255	0	0	dark
Grey	128	128	128	dark
Violet	148	0	211	dark
Brown	150	75	0	dark
Orange	255	127	0	bright
Yellow	255	255	0	bright
White	255	255	255	bright

II. EXPERIMENT

A. Material & Methods

An experiment, consisting of two different parts, was conducted in 2 ways: as a laboratory situation and as an online survey. In order to maximize the number of participants, it was necessary to adjust the experiment as an online survey. 22 synaesthetes with sound-colour synaesthesia participated in the experiment (4 males, 18 females); including 10 associators and 1 projector (rest of subjects could not give a concrete answer to this question).

Experiment 1:

3 different kinds of noise bursts (white, pink, brown) were consecutively presented, intercepted by a sine tone and a sawtooth tone. Every sound had 7 seconds duration. The sounds were presented in the following order: white noise, sine tone, pink noise, sawtooth tone, brown noise. For every stimulus 7 colours were presented, which were the same for all stimuli: white, black, pink, brown, red, yellow and violet.

Experiment 2:

6 different sounds were presented. The first three were pure tones of 3 different frequencies: 50Hz (low), 700Hz (middle), 3000Hz (high). The last three were complex tones of 3 different frequency ranges: 50-150Hz (low range), 500-700Hz (middle range) and 1500-2500Hz (high range). The first complex tone was composed of 5 sine tones with frequencies 50, 75, 100, 125 and 150Hz respectively, the second complex tone was composed of 5 sine tones with frequencies 500, 550, 600, 650 and 700Hz respectively and the third complex tone was composed of 5 sine tones with frequencies 1500, 1750, 2000, 2250 and 2500Hz respectively.

For the online survey the low frequencies were separately configured so that they could be reproducible from any kind of laptop pc or desktop pc loudspeaker system (first pure tone: 100Hz, first complex tone of 5 sine tones with frequencies 100, 125, 150, 175 and 200Hz). All stimuli were normalized at -3dB.

8 colours were proposed for every stimulus in the following order: white, black, green, orange, red, yellow, violet and blue.

For the laboratory situation following equipment was used: 2 Genelec loudspeakers for sound reproduction, 1 Genelec subwoofer for low frequency reproduction. All sound processing was made using the programs Cubase and Max/MSP.

B. Experimental Procedure

For the whole experiment the subjects were instructed firstly to be as much as spontaneous as possible with their answers and secondly to consider colours without saturation or any shading. It was mentioned that the given colours referred to colour categories. In Experiment 1 (noise bursts) the subjects were asked to match a colour, from the colours given, to the sound they heard. The colour chosen should be representative of the synaesthetic experience, evoked by the sound heard. In Experiment 2 (pure tones), the subjects were asked to choose for every sound a colour that matched their synaesthetic experience the most.

If a colour was not listed, subjects were allowed to write it down. Every sound could be repeated as many times as the test person wanted.

III. RESULTS

A. Experiment 1: Noise bursts vs. sine and sawtooth tones

Hypotheses

Two main hypotheses were tested. The first hypothesis was, if the timbre or the pitch of the sound can influence the chroma and colour plurality of the synaesthetic experience. If the timbre or the pitch of the sound affects the chroma and the colour plurality then we can observe firstly if different spectrums or pitches can conclude to a) an achromatic or chromatic or b) a uni- or multi-colour experience. That means that differences in the experience are expected when hearing to noise, a sine and a sawtooth tone.

The second hypothesis tested was, if the type of noise can affect the chroma and the colour plurality. The spectrums of white, pink and brown noise are perceived much similar and that would suggest that no differences should be observed on the chroma and the colour plurality of the experience.

Statistical Analysis

A chi-square (χ^2) test was conducted in order to observe if there is a relationship between the type of sound and the chroma. A significant association was found between the type of sound and the chroma of the sensation: $\chi^2(2) = 26.649$, $p < .001$ (Cramer's $V = 0.464$, $p < .001$). This seems to represent the fact that based on the odds ratio; the odds of achromatic colour were 8.35 higher if evoked by a noise than by a sine tone or a sawtooth tone. A significant correlation was also observed between the type of sound and the chroma [$r = 0.427$, p (2-tailed) $< .001$]. Synaesthetic experience is mostly achromatic when hearing to noises but more likely to be chromatic when hearing to sine or a sawtooth tone, as shown in Fig. 1.

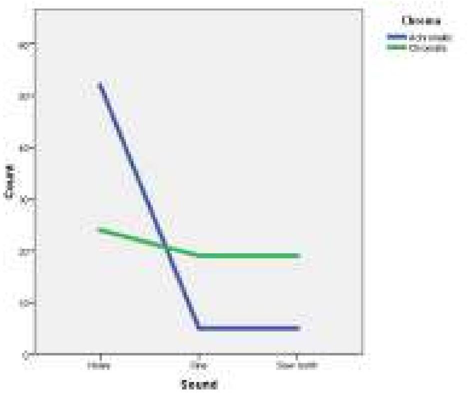

Figure 1. Effect of sound on chroma of the visual experience.

The colours grey (36%) and white (24%) were chosen the most, when hearing to noise bursts. Colours, such as yellow and violet, were chosen the least in contrast to red, which was not chosen at all, as shown in Fig. 2.

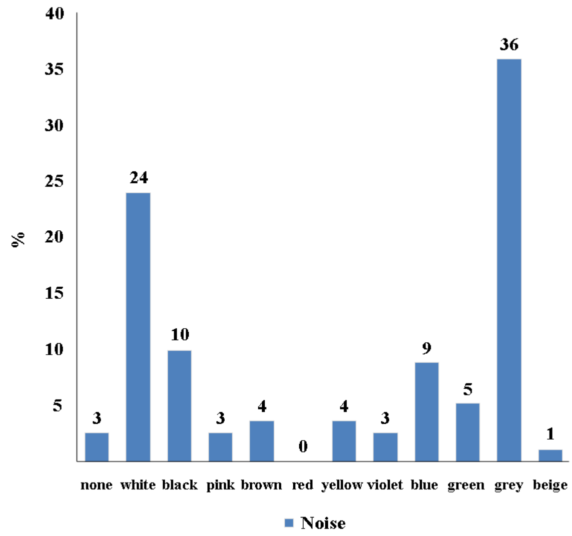

Figure 2. Colours chosen, when hearing to noise bursts

When hearing to sine tone yellow (24%) and red (21%) are the most chosen, whereas blue, green and grey are chosen the least. The colours brown or beige are not mentioned in any answer (e.g. Figure 3). When hearing to sawtooth tone green (24%) and brown (18%) are the most chosen, in contrast to white, violet and blue, which are chosen the least. Pink and beige are not mentioned in any answer (e.g. Figure 4). That confirms that achromatic colours represent the synaesthetic experience the most, when hearing to noises, and chromatic colours, when hearing to sine and sawtooth tones.

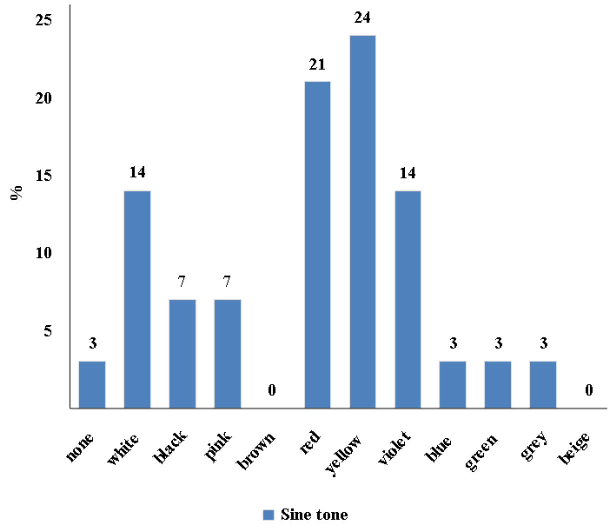

Figure 3. Colours assigned, when hearing to a sine tone.

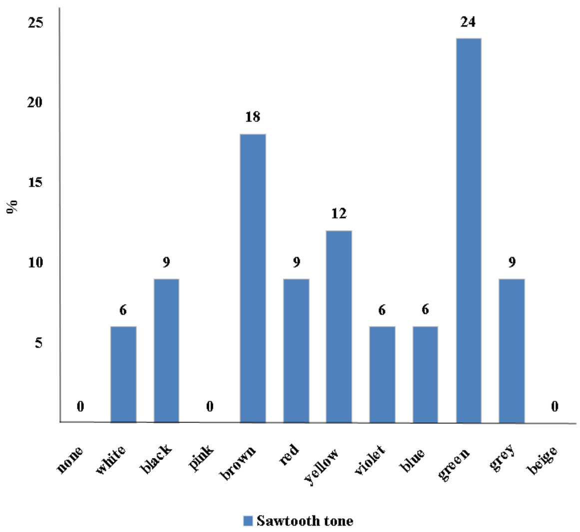

Figure 4. Colours assigned, when hearing to a sawtooth tone

It was also examined if the type of noise influences the colour plurality by conducting a chi-square (χ^2) test, which showed a significant association between the type of noise and the plurality of colour: χ^2 (2) = 7.141, p < .05 (Cramer's V = 0.334, p < .05). This seems to represent the fact that, based on the odds ratio, the odds of unicolour experience were 5.2 times higher if the noise was white than pink. Although it is more likely that when listening to white and brown noise the experience consists of one colour, pink noise has the tendency to consist of more than one colour (e.g. Figure 5).

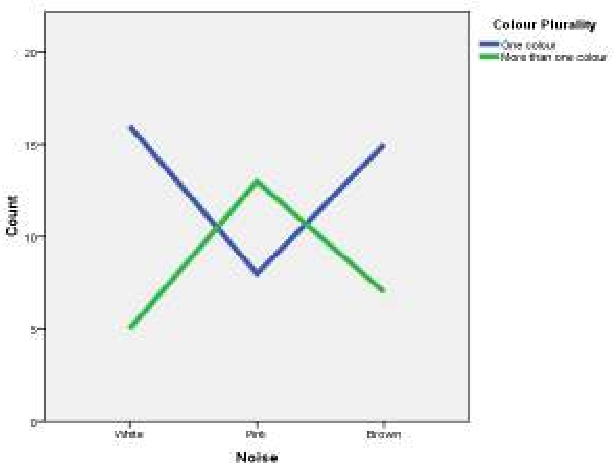

Figure 5. Effect between the type of noise and the number of colours present in the visual experience.

White and brown noises are highly matched to one colour (73% and 68% respectively) in contrast to pink noise which evokes either 2 or 3 colours (e.g. Figure 6).

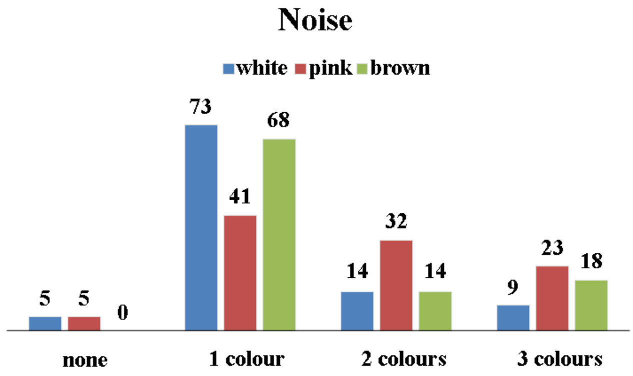

Figure 6. Colour plurality for different noise bursts

Type of sound affecting chroma

A significant influence of the type of sound on chroma was found and specifically between noise and sine tone as well as noise and sawtooth tone but not between sine and sawtooth tone.

All sounds have different acoustical spectral and temporal characteristics, such as different centroid, different attack and decay time; therefore we can talk about sounds that have different spectrums. But the most important obvious difference, between the given stimuli, is the pitch. On one hand noise contains all hearable frequencies (20Hz – 20 kHz), on the other hand sine and sawtooth tone have both a defined hearable frequency, in this case a frequency of 440Hz.

If we assume that the timbre influences chroma, when hearing to noise and pure tones, then differences should be also expected between sine and sawtooth tone, but no differences were found. We could assume that timbre affects only a part of the chroma and that is the representation of the chromatic experience. That could explain why for synaesthetes identical instruments (for example piano or violin) have different colours.

But frequency seems to play a key role on the experience and how the synaesthetic mechanism processes that kind of information. Undefined perceived pitch (noise) can evoke an achromatic experience, whereas a defined perceived pitch a chromatic experience. That means that the mechanism maps undefined pitch to a visual representation in which hue is absent, whereas defined pitch is mapped to a visual representation in which hue is present.

Type of noise affecting colour plurality

The type of noise affects the colour plurality of the synaesthetic experience. Although white and brown noises are represented uni-colour, pink noise is represented multi-colour and the representation consists either of 2 or 3 achromatic colours.

White, pink and brown noises have similar acoustical characteristics: a) they contain all audible frequencies and b) they have constant amplitude. The only difference between these noises is the power density. White noise has a flat frequency spectrum and an equal power density for every frequency, pink noise has a power density which decreases by -3dB for every octave (1/f) and brown noise has a power density which decreases by -6dB for every octave ($1/f^2$). This difference in power density changes the centre of mass of the spectrum (spectral cendroid) and it is responsible why white noise can be perceived as rough in contrast to pink or brown noise which can be perceived as soft. As it seems synaesthetes do not observe auditory differences between white and brown noise or pink and brown noise, but the difference in the power density between white and pink noise (-3dB) is easier to detect/perceive. It is possible that this slightly hearable change of the density can affect the colour plurality of the experience.

B. Experiment 2: pure tones vs. complex tones

Hypotheses

2 main hypotheses were tested. The first hypothesis was, if the pitch of a pure tone (low, middle or high) will affect the brightness of colour of the synaesthetic experience. If so, it could be assumed that for low pitched tones, dark colours are being chosen whereas for high pitched tones bright colours. The second hypothesis was, if the sound plurality can affect the colour plurality of the experience. It can be assumed that a pure tone can evoke a uni-colour experience whereas complex tones can evoke a multi-colour experience. If so, it is possible that the synaesthetic perception functions additively. Every sound causes a different coloured experience and different frequencies are not summed up, but separately processed. The sound plurality describes if the sound (stimulus) consists of one pure tone or complex tones (5 sine tones).

Statistical Analysis

In order to investigate if there is any relationship between pitch and brightness of colour a chi-square (χ^2) test was conducted. The test showed that there is a significant association between the pitch and brightness: χ^2 (2) =7.767, p < .05 (Cramer's V = 0.227, p < .05). A negative correlation was also observed between the two variables [r = -0.227, p (2-tailed) < .01]. Low and middle pitch was matched to dark colours but for high pitch the colours chosen were mixed, either bright or dark, as shown in Fig. 7.

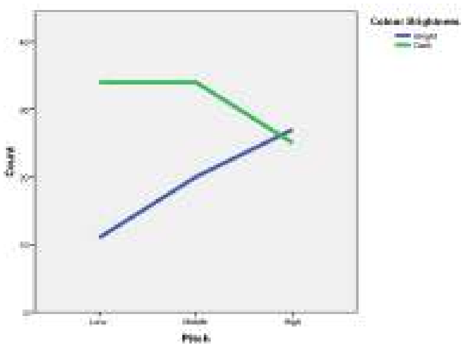

Figure 7. Effect of pitch on colour brightness of the experience

Low pitched sine tone (50Hz) evokes black (19%), brown (14%) and violet (14%), middle pitched sine tone (700Hz) evokes white (21%), yellow (18%) and violet (18%) and high pitched sine tone (3000Hz) evokes yellow (29%), white (23%) and green (19%) (e.g. Figure 8). When hearing to complex tones, the distribution is similar, depending on the frequency range of the sound. For low frequency range complex tones (50-150Hz) black (28%), green (24%) and brown (13%) are being chosen the most. Middle frequency range of the sound (500-700Hz) evokes green (22%), black (22%) and brown (14%) and high frequency range of the sound (1500-2500Hz) evokes yellow (17%), orange (14%), green (14%) and violet (14%) (e.g. Figure 9).

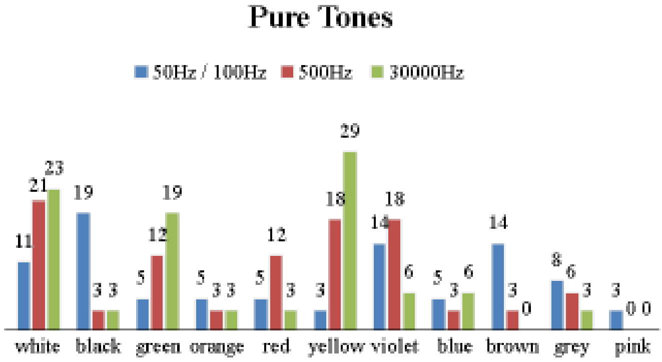

Figure 8. Colours assigned, when hearing to pure tones (number represent %).

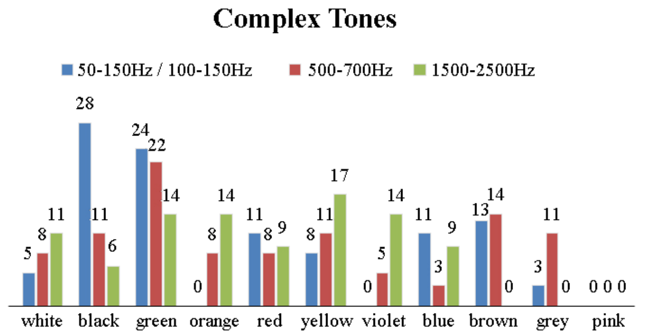

Figure 9: Colours assigned, when hearing to complex tones (numbers represent %).

Table 2 shows the most chosen colours in general from low to high frequency for pure or complex tones:

Table 2. Sum up of colours most chosen for different frequency ranged

	Pure Tones	Complex Tones
Low	Black, brown, violet	Black, green, brown
Middle	White, yellow, violet	Green, black, brown
High	Yellow, white, green	Yellow, orange, green, violet

In order to examine if the plurality of sound influences the plurality of colour a chi-square (χ^2) test was conducted, showing that there is a significant association between the two variables: χ^2 (1) = 3.967, p < .05 (Phi = 0.180, p < .05). Based on the odds ratio, the odds of the colour plurality were 2.09 times higher when there was only one pure tone present than complex tones.

A positive correlation was observed between the two variables [r = 0.180, p (2-tailed) < .05]. It is clear, that a pure tone evokes a uni-colour experience whereas a complex tone evokes a multi-colour experience, as shown in Fig. 10.

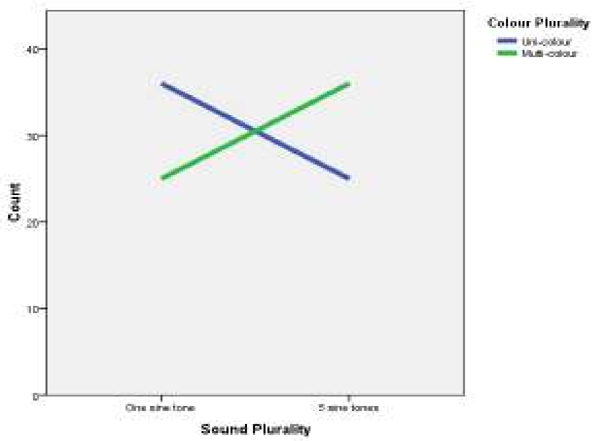

Figure 10. Effect of sound plurality on the colour plurality of the sensation

When listening to a pure tone mostly only one colour is being evoked; for low pitched sine tone 1 colour (45%) in contrast to 2 colours (27%), for middle pitched sine tone 1 colour (55%) in contrast to 2 colours (27%) and for high pitched sine tone 1 colour (64%) in contrast to 2 colours (23%) (e.g. Figure 11). For a complex tone of low pitched range between 50Hz and 150Hz 1 colour (36%) or 2 colours (32%) can be evoked. For a complex tone of middle pitched range between 500Hz and 700Hz also 1 colour (41%) or 2 colours (41%) can be evoked but for a complex tone of high pitched range between 1500Hz and 2500Hz 2 colours (50%) rather than 1 colour (36%) are being evoked (e.g. Figure 12).

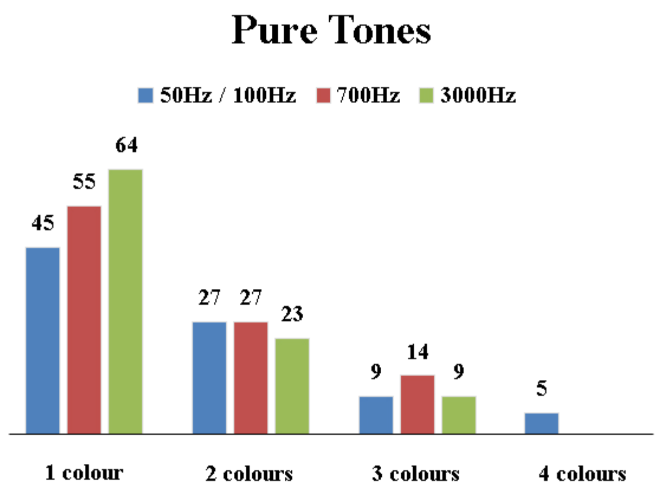

Figure 11. Colours present in the synaesthetic experience, evoked by pure tones (numbers represent %).

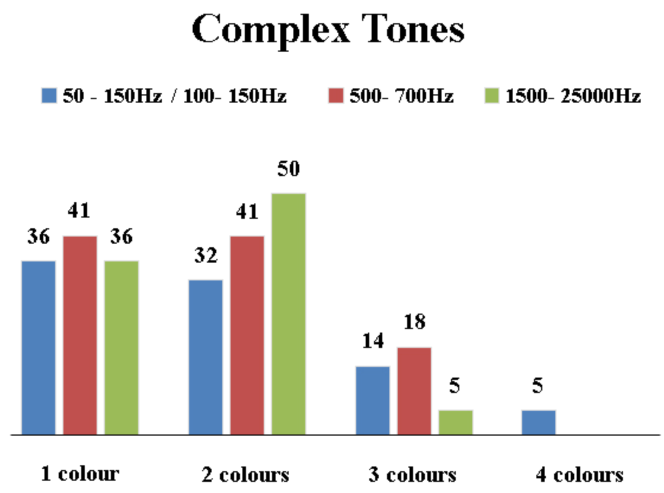

Figure 12. Colours present in the synaesthetic experience, evoked by complex tones (numbers represent %).

Pitch affecting colour brightness

The perceived frequency range of the sine tone affects strongly the representation of colour during the experience. When hearing to a low frequency sine tone (100Hz) dark colours are most chosen, whereas when hearing to a high frequency sine tone (3000Hz) bright colours are most chosen. This correspondence confirms the theory (Marks, 1974, 1975) that these correspondences are made either by synaesthetes or non-synaesthetes. The subjects assigned increasing pitch to increasing brightness of colour (luminance); low pitch – dark colour, high pitch – bright colour. As it seems the neurological mechanism, triggering the synaesthetic experience, encodes/decodes pitch information and maps it to colour brightness. This mapping depends on the distribution of the total power between low and high frequencies, a distribution which is responsible for the perception of sound as bright or dull.

Terhardt (1972) differentiates pitch between virtual and spectral. Virtual pitch consists of harmonics and near-harmonics and spectral pitch corresponds to individual hearable pure-tone characteristics. The crossover from virtual to spectral pitch is by approximately 800Hz. Human pitch perception works differently at low and at high pitches. On one hand our hearing mechanism can count out of the cycles of a periodic tone (periodicity/time theory), process applied when hearing to low frequencies, and on the other hand specific parts of the basilar membrane are being stimulated for specific frequencies (place theory), process applied when hearing to high frequencies. In middle ranges both mechanisms operate. Depending on which mechanism is being used (time or place theory), the mapping of synaesthetic mechanism is changing. So it could be suggested that time theory affects the mapping between pitch and colour brightness, making the visual colour representation dark and place theory affects the mapping by making the visual colour representation bright. Middle pitch ranges are more unclear, there can be dark or bright because the synaesthetic mechanism can not recognize which hearing mechanism is being used for the encoding/decoding of pitch information.

Sound plurality affecting colour plurality

Hearing one stimulus at a time evokes a uni-colour experience. It would be expected that if the sound consists of two elements (for example two pure tones), synaesthetic experience should be consisted of two colours; if the sound consists of five elements then the experience should be consisted of five colours and so on. But that doesn't happen. We saw that when hearing to five pure tones simultaneously, two or three colours are being evoked, suggesting that synaesthetic perception is additive. That means that the synaesthetic mechanism does not map the number of sound sources heard proportionally to number of colours (colour plurality). It is not a one-to-one mapping. By low frequencies we may hear successive elements of a sound (like the cycles of a wave) without perceiving just one pitch. The synaesthetic mechanism adds these elements and sums up the different frequencies. It can be assumed that by the stimulus of five sine tones of variable frequencies, the resulting sound is characterized by the presence of fundamental frequencies and overtones. It is possible that for a sound consisted of five sine tones, such as 100, 125, 150, 175 and 200Hz respectively, the fundamental frequency 100Hz is perceived as a ground tone and the rest frequencies as overtones, meaning that the ground tone is mapped to one colour and the overtones to an extra colour or two extra colours, depending on the number of partials.

What is also interesting is that when the pitch range rises but the sound consists of more than one element, only in this case, the synaesthetic experience changes to multi-colour. Sound plurality affects the colour plurality but only in combination to high pitched sounds (above 1500Hz).

We conclude that pitch plays a significant role in the synaesthetic mechanism and the visual representation of the experience. Defined or undefined pitch determines if there is a presence of hue in the experience (chroma). The power density of the sound, when pitch is undefined, can influence the colour plurality. Depending on which auditory mechanism is being used for the processing of pitch and the distribution of the total power between the frequencies, hue can be present or not during the visual sensation. Complex tones with frequencies above 1500Hz, when present in sound (sound plurality), conclude to a multi-colour sensation consisting of assignment of one colour for the fundamental and one or two colours for the overtones (e.g. Figure 13, Figure 14 & Figure 15). The timbre of the sound seems to influence not the appearance of chroma, since chroma is activated by the frequency heard, but the chromatic content of the experience. For a synaesthete a clarinet can be red or a trumpet can be yellow. In this case, the experiences are both chromatic, contain colour, but it is the pitch which triggers the synaesthetic experience. It is suggested that the pitch triggers the experience and is responsible for the appearance of chroma or not and the timbre manages the chromatic content of the experience.

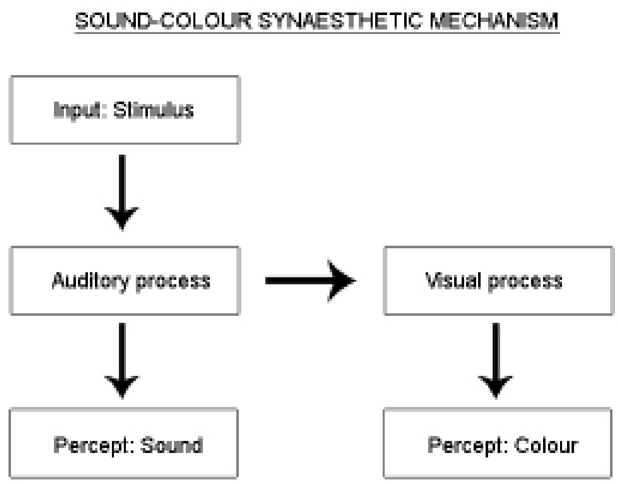

Figure 13. Synaesthetic mechanism triggered by auditory input

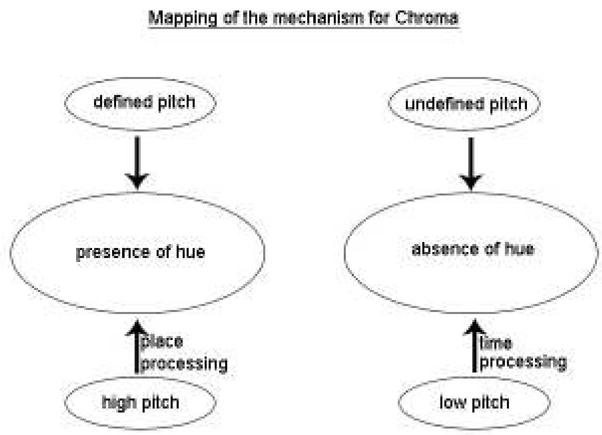

Figure 14. Chroma is mapped according to processes of pitch perception

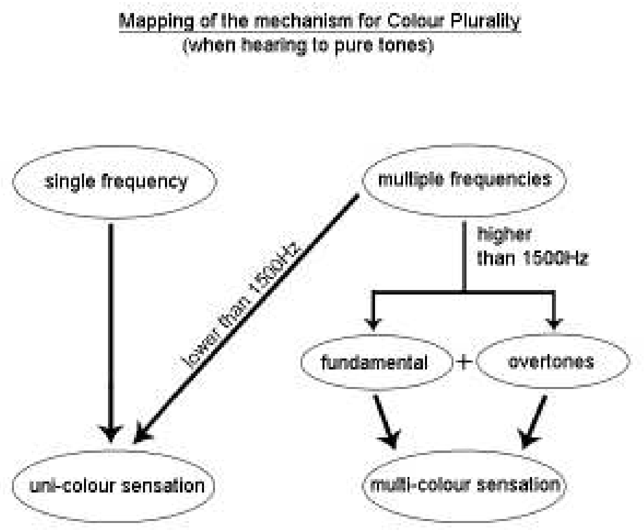

Figure 15. Coloured synaesthetic experience influenced by frequency range.

IV. CONCLUSION

In this paper, it is shown that perceptual pitch processing is the first station of a complex process leading to visual sensation, evoked by sound in genuine sound-colour synaesthesia. If we want to find out exactly how the synaesthetic mechanism functions, it is very important to understand, how the auditory information is being translated and mapped by the mechanism, perceptually and conceptually, therefore more experiments are necessary to be carried out. The last 10 years, research concentrates more on grapheme-colour synaesthesia, the most common type, and less on sound-colour synaesthesia, a rare type. But if research continues, even for not those common types of synaesthesia, then we have the chance to fully understand cross-modal interactions and processes, helping us to get more information about the human brain.

ACKNOWLEDGMENT

The author kindly thanks the UK Synaesthesia Association, the Synaesthesia Mailing List (S. Dean) and the German Synaesthesia Forum (http://www.synaesthesieforum.de/) for distributing the online survey to their members.

REFERENCES

Baron-Cohen, S., & Harrison, J. (1997). *Synaesthesia: classic and contemporary readings*, Cambridge, Mass.: Blackwell.
Baron-Cohen, S., & Harrison, J. (1994). Synaesthesia: An account of colored – hearing. *Leonardo: Journal of the international society for the Arts, Sciences and Technology, 27,* 343 – 346.
Behne, K. E., (1991). *Am Rande der Musik: Synästhesien, Bilder, Farben.....* In *Musikpsychologie: Jahrbuch der Deutschen Gesellschafte für Musikpsychologie, 8,* 94 – 120.
Bleuler, E., & Lehmann, K., (1881). *Zwangsmäßige Lichempfindungen durch Schall und verwandte Erscheinungen auf dem Gebiet der anderen Sinnesorgane*, Leipzig: Reisland.
Cynader, M.S., Andersen, R.A., Bruce, C.J., Humphrey, D.R., Mountcastle, V.B., Niki, H., Palm, G., Rizzolatti, G., Strick, P., Suga, N., von Seelen, W. & Zeki, S. (1988). General principles of cortical operation. In: P. Rakic & W. Singer (Eds.), *Neurobiology of Neocortex* (pp. 353-371). New York: John Wiley.
Cytowic, R. E. (1989). *Synesthesia, a Union of the Senses.* New York: Springer.
Cytowic, R. E. (1998). *The Man who tasted Shapes*, Cambridge: MIT Press
Grossenbacher, P. (1997). Perception and sensory information in synaesthetic experience. In S. Baron-Cohen & J. Harrison (Eds.), *Synaesthesia: Classic and contemporary readings* (pp. 148-172). Oxford: Blackwell.
Marks, L.E. (1974). On Associations of Light and Sound: The Mediation of Brightness, Pitch and Loudness. *American Journal of Psychology, 87*, 173 – 188.
Marks, L.E. (1975). On Colored – hearing Synesthesia: Cross – modal translations of Sensory Dimensions. In Psychological Bulletin, 82, 303 – 331.
Marks, L.E. (1978). The *unity of the senses: interrelations among the modalities*, New York: Academic Press.
Maurer, D. (1993). Neonatal synesthesia: Implications for the processing of speech and faces. In B. de Boysson et al. (Eds.), *Developmental Neurocognition: Speech and face processing in the first year of life* (pp. 109-124). Kluwer Academic.
Ramachandran, V.S., & Hubbard, E.M. (2001a). Psychophysical investigations into the neural basis of synesthesia. *Proceedings of the Royal Society of London B, 268,* 979-983.
Ramachandran, V.S., & Hubbard, E.M. (2001b) Synesthesia—a window into perception, thought and language. *Journal of Consciousness Studies, 8,* 3-34.
Riggs, L. A., & Karwoski, T.. (1934). Synaesthesia. *British Journal of Psychology, 25,* 29 – 41.
Terhardt, S. (1972). Zur Tonhöhewahrnehmung von Klängen. I. Psychoakustische Grundlagen. *Acustica: International Journal on Acoustics, 26,* 173-186.
Wellek, A. (1929). Das Doppelempfinden in der Geistesgeschichte. *Zeitschrift für Ästhetik und allgemeine Kunstwissenschaft, 23,* 14 – 42.
Werner, H. (1966). Intermodale Qualitäten (Synästhesien). *Handbuch der Psychologie, 1,* 278-303.