Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Computer Science

Sabina Niewiadomska

Web-based research on cross-modal correspondences between colour and sound.

Master's thesis in Applied Computer Science
Supervisor: Mariusz Nowostawski, Philip Green, Dominik Osinski
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Preface

The following dissertation is a Master's thesis in Applied Computer Science at NTNU Gjøvik carried out in the spring semester of 2019. The first idea of the project was brought up during IMT4894 Advanced Project Work. However, the experimentation in the discipline has begun at IMT4315 Colour in Interface Design, encouraged to explore colour to sound correlations by Professor Philip Green. This work has spawn from an abstract accepted for *AIC 2019 Midterm Metting: Color and Landscape conference* titled "*Colour to sound translations and world perceivability*" [1]. This dissertation would have never be created without the encouragement of Dominik Osiński, Associate Professor at NTNU Trondheim in the middle of spring semester 2019 and is supervised by Associate Professor Mariusz Nowostawski from NTNU Gjøvik. The thesis focuses on web-based research on cross-modal correspondences between colour and sound, also covers colour sonification methods, sensory substitution devices and sensory substitution software. This Master Thesis report assumes the reader has prior knowledge in colour theory and computer science, especially in web browser technologies.

01-06-2019
Sabina Niewiadomska

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S.N.

Abstract

Cross-modal correspondences between colour and sound or sound and colour are the basis for the colour sonification methods used in some categories of sensory substitution devices or sensory substitution software. This Master Thesis explores sonification methods, sensory substitution devices and software, dedicating particular interest to how the cross-modal correspondences can be researched through controlled laboratory study, Virtual Reality or web-based research. The advantages and disadvantages of Web-based researches are analysed in the delicate context of psychophysiological studies. The study presents interesting results regarding the connection between sound frequency and hue, saturation and lightness, gives recommendation about further research in cross-modal correspondences, comments on the state of Web APIs and Web Audio API in a psychophysiological research context, gives an overview of modern web-based technologies (such as Vue.js, Tone.js, Firebase) and their use in psychophysical studies.

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1 Introduction

1.1 Topic Covered

Cross-modal correspondences between colour-sound and sound-colour are the foundation for the development of colour sonification methods used in sensory substitution devices and software. The study of cross-modal correspondences was traditionally carried out in controlled laboratory experiments. However, with the current technological developments, this research might also be carried out through web-based research or Virtual Reality.

1.2 Problem description

"Sensory Substitution Devices" (SSD) (see Chapter 2.2), as a potentially low-cost and accessible tool, have the potential to aid visually impaired people (see Chapter 2.1) as part of a non-invasive rehabilitation. The definition of visually impaired covers a broad spectrum: from completely blind subjects [3] to subjects affected by colour vision deficiency [4] (e.g. SSD can support colour recognition to compensate the effects of colour blindness).The main challenges of SSD development are the ease of use and costs. The device has to be easy to wear or carry as well as simple to operate, with special care needed to avoid sensory overload or perceptual illusions [5]. Auditory-visual and tactile–visual SSDs transform "visual information into an auditory or tactile representation" [3], this complex process should be carefully thought out. The auditory representation used by the previous auditory-visual SSD is often arbitrary and non-standardised. Finding usable and enjoyable sonification method for colour to sound SSD has the potential to push completely change the quality of such SSD increasing user acceptance and effectiveness.

1.3 Justification, Motivation and Benefits

Over three hundred years ago Isaac Newton proposed a seven tones colour to sound scale based on his scientific studies [6], soon after colour to sound scales were proposed by other scientists, musicians, artists and synesthetics [7], [4], [8]. Colour to sound scales in art has often taken the form of musical instruments, such as "colour organs" [9], [10] or, as opposite relation, the form of painting inspired by music [8]. Nowadays, thanks to technological development, colour to sound scales are used by researchers for colour sonification in sensory substitution devices such as Soundview [11], Eyeborg [4], Kromophone [12], See ColOr [13], ColEnViSon [14], EyeMusic [15], VBTones [16] or Colorophone [17]. The goal of such devices is to support blind or colour blind subjects. It becomes therefore crucial to choose a sonification method able to support the representation of the most important visual information without provoking sensory overload [5]. Studies of colour to sound association should be at the base of sonification systems. For this very reason, a solution which allows the researchers to set to up an experiment quickly and possibly invite participants remotely is key to the development of a better colour sonification method.

The proposed solution is, to the author best knowledge, the first tool which focuses only on studying colour to sound associations through a browser. It has the aim to support the research in colour sonification aiding the investigation of cross-modal correspondences and allowing the researchers to choose freely different perspectives when approaching the research.

1.4 Purpose of the Study

The purpose of this study is to create a tool which allows researchers to carry out multidimensional studies (hue - chroma - lightness, pitch (frequency)) in which the participants builds its individual colour to sound map. Thanks to the "crowd-sourced" data collection enabled by this tool, the researchers will be able to understand better how a sensory substitution device can represent visual reality as a sound. This study could form the basis for further advancements in colour sonification methods.

1.5 Research questions

Colour sonification research questions

R1: How research in cross-modal correspondences could be improved?

The research questions listed above are referring to the basis which should be considered in the creation of a colour sonification research; enabling a qualitative study of the methods for colour sonification proposed by other researches, focussing on which music scale was used to represent the colour, why it was used and the evaluation of its use.

Implementation research questions

R2: How to implement 4-dimensional (hue - lightness - saturation - frequency) experiment in which participants are building individual colour to sound mappings?

- What are technical challenges of creating a solution which should support building colour-to-sound scale?

These are the main research questions, and they will guide the implementation of a technological solution. The research will be carried out as a series of qualitative studies which will evaluate existing colour sonification methods and related technological possibilities and limitations to consider during the implementation of the method.

1.6 Contributions

This thesis contributions to its field knowledge can be organised into three domains: research of colour sonification methods, implementation of the research tool for the optimisation of colour sonification methods and the research revolving around the user experience in the research and research tool design.

Colour sonification research questions

This section of the thesis's work will provide an overview of different colour sonification methods. The overview attempts to describe the sonification methods and their scientific background as well as provide recommendations of what makes a good sonification method.

Implementation research questions

This thesis includes analysis of thechnologies such as VR and web in context of research in cross-modal coresspondences between color-sound and sound-colour and the development of the first tool to perform web-based research on sonification methods.

User experience research questions concerns implementation and research design

This part of the thesis will provide an analysis of what concerns the user experience of the research tool design as well as user experience and interface design recommendations for web-based colour sonification method research tools.

1.7 Thesis outline

Chapter 2 Related Work

The Related Work Chapter introduces the reader to the problem of colour blindness and blindness, then provides an overview of sensory substitution devices and colour sonification methods used in the devices. Next, the reader is introduced to the different colour scales as well as the research methodology in cross-modal correspondences and the scales build upon those researches.

Chapter 3 Methods

The Methods Chapter provides an overview of psychophysiological research design such as controlled laboratory experiments, Virtual Reality as substitution of controlled laboratory experiment and web-based research. Then the web-based research is analysed and evaluated. The methods chapter includes technology assessment and justification for the developed solution, as well as evaluating the Web Audio API and its framework Tone.js, the Web APIs in the context of psychophysiological research. This chapter also describes a web-based cross-modal correspondences experiment setup and its justifications.

Chapter 4 Implementation

The Implementation Chapter describes the details of the client-side web-based research implementation with the use of Vue.js as the main framework.

Chapter 5 Experiment Results

The Experiment Results Chapter describes the results of the cross-modal correspondences studies between colour and sound.

Chapter 6 Results: web based research evaluation

The Results Chapter concentrates on the evaluation of the web-based research.

Chapter 7 Discussion

The Discussion Chapter provides an interpretation of the results, recommendations and improvements.

Chapter 8 Conclusion

The Conclusion Chapter sums up the contributions of the Master Thesis and suggests further work.

1.8 Keywords

mobile web music, mobile web applications, web technologies, HTML 5, sensory substitution, colour, sound, music computing – systems, cross-modal correspondences

2 Related Work

2.1 Colour blindness and blindness

According to Britannica Academic colour blindness is the "*inability to distinguish one or more of the three colours red, green, and blue*" [18]. The cones, a kind of photoreceptor mainly distributed in the fovea centralis, the central area of the retina, are responsible for colour vision. Different types of cones absorb light at different wavelengths and respond to different colours: blue-violet, green and red.

Types of colour blindness

Colour vision occurring without any dysfunctions in the cones is called **trichromacy** (or trichromatism). When one type of cone is dysfunctional/absent it is called **dichromacy** (dichromatism), and when two or three type of cones are dysfunctional it is called **monochromacy** (monochromatism). Forms of dichromacy are protanopia (inability to perceive "red" light), deuteranopia (inability to perceive "green" light), tritanopia (inability to perceive "blu" light or to distinguish between "blue" and "yellow"), tritanomaly (reduced sensitivity to "blue" light) [18].

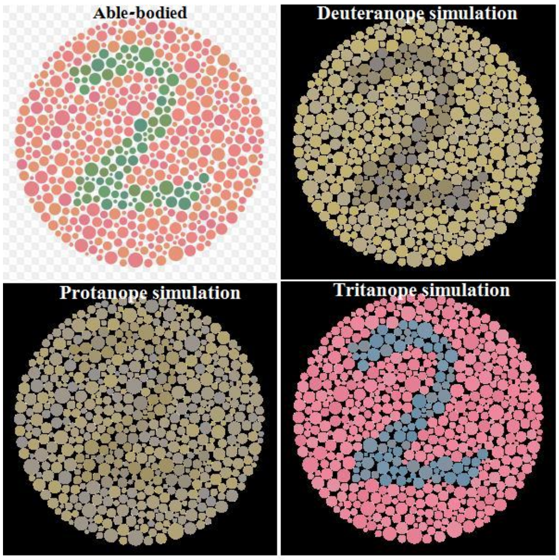


Figure 1: Example of color perception simulation based on Ishihara test. Source of picture: Wikipedia Media [19], CC BY-SA 3.0

Blindness

A more severe dysfunction in vision is blindness, defined as a "*transient or permanent inability to see any light at all (total blindness) or to retain any useful vision despite attempts at vision enhancement (functional blindness)*" [20]. Vision impairment has few levels: near-normal vision, low vision, near-blindness and total blindness. For some type of blindness, treatment is available. Otherwise, a variety of low-vision aids are available, other senses have the tendency to compensate the loss provoked by the vision impairment [20].

Consequences

A great portion of the information that we (human society) embed in our environment is colour-coded. Examples are the colours of traffic lights, traffic signs, subway lines and much more. This use of colour is common also to front-end frameworks, such as Bootstrap, whose documentation is recommending to categorize information relative to success/completion with green, a danger with red, warning with yellow and primary text or information with blue [21]. Colour alone without the addition of redundant graphical elements such as icons or text could result in an information loss. Similarly, when colour is part of the language, such as in the expressions" Red Alert" or" Green Party", the meaning could differ for visually impaired subjects. Another example is colour coding in products. For example, the Norwegian brand "Go' morgen" is colour coding the information about the taste of yoghurts, white is natural, strawberry is red and so on. Neil Harbisson, subject with achromatopsia, as a child tried to correlate a colour to characteristics of people, for example, blue was chosen to represent a particularly intelligent friend, pink was associated with a "hippie girl". Later Neil Harbisson started to use a device called "eyeborg" which allowed him to hear colours [4]. The "Eyeborg" is a sensory substitution device which is mapping colours to the sounds. Researchers have created many other different sensory substitution devices, which in many ways are trying to substitute visual information (see chapter 2.2).

2.2 Sensory Substitution Devices

A **Sensory Substitution Device** is a tool "*designed to convey visual information to the visually impaired by systematically substituting visual information into one of their intact senses*" [3]. **Sensory substitution devices (SSDs)** are "*non-invasive human-machine interfaces which, for a blind subject this means to transform visual information into auditory or tactile representations using a predetermined transformation algorithm*" [3]. SSDs can be used by blind subjects as well as colour blind subjects [4], while in the case of blindness, the use might be more focused on rehabilitation [3]. There are two types of SSD, one which allows visual-to-tactile substitution and second, which allows visual-to-auditory substitution [22]. This thesis focuses on visual-to-auditory substitution devices.

2.2.1 Sensory Substitution and Augmentation Overview

Sensory Substitution Devices are usually developed alongside the software, but sometimes only the software (or algorithm) is developed, in this case only the sonification method has to be tested. In this overview terms from music theory, acoustics science or colour science are explained to allow easier comprehension, still, researchers and authors of the literature are not using a standardised and consistent language, mixing acoustics terms with music terms (e.g. Sound frequency can be referred as called pitch, sound frequency and fundamental frequency). This overview is attempting to maintain the original language used in the papers and dissertations explaining the specific terms when necessary.

The vOICe, VBTones

The vOICe is an auditory-substitution-of-vision device which can help with locomotory guidance, localisation, pointing in space and object recognition [22]. The use of the vOICe based tones (VBTones) are also mentioned in [16] where images are represented as rows and pixels to which are assigned to sound frequency and sound amplitude (loudness). The sound amplitude depends on pixel brightness. After scanning the image, the sound is generated column by column.

HueMusic

HueMusic is used for conversion of 2D images into sounds, the tool recognises eight hue value (black, red, yellow, green, cyan, blue, magenta, white) and associate with them eight timbres (seven timbre sounds, for example: "*fire for red and another a breaking glass sound for magenta*", and silence for white) [23].

Kromophone

The Kromophone maps colour to frequencies. The device provides three modes RGB, HSL and default RGBYW. The RGB mode presents colour as three main frequencies based on three main channels of RGB (red, green, blue). Interestingly Kromophone is using stereo channels to locate the analysed colour in the sound field panning the sound from the left to right channel. To create the sound frequencies, Kromophone adopts an algorithm which multiplies simple sinusoidal frequencies according to the authors choice. Therefore red can be heard as high pitch in the right headphone; green can be heard in the centre whit a medium pitch and blue in the left headphone as a low pitch sound. In HSL mode hue is mapped to pitch, saturation to panning (placing of sound in the left, middle or right) and luminosity to volume. The default RGBYW (red, green, blue, yellow, white) mode is mapping colour to pitch, panning, tone (tone has more sound characteristics than pitch (sound frequency) for example timbre) and volume. Red has high pitch and is placed in the right channel, characterised by a trumpet-like tone. Green has medium pitch and is also placed in the right channel with a violin-like tone. Blue has a low pitch, is placed on the left and has a trumpet-like tone. Yellow has a high pitch, is placed in the left channel and has a ukulele-like tone while white is high-pitched sound placed in the middle. The intensity of the colour is mapped to the volume of the resulting sound[12].

The See Color and SonarX

The See Color is a software which helps to receive information from images (images, stored video, live video) about the range of colours, presence or absence of light sources or location and shape of objects. HSV (hue, saturation, value) colours are mapped to pitch (fundamental frequency), timbre (defined as signal's spectral envelope, sinusoidal wave for low saturation value, square wave for highest saturation value) and loudness. The value represents the intensity of colour [13]. A similar algorithm is using SonarX, a tool for analysing still images and videos, to represent characteristics of the environment without vision. The tool converts hue, saturation and value into pitch (fundamental frequency), timbre and loudness [24].

Creole

Creole is a tablet-based SDD which maps colours to sounds based on established cross-modal correspondences (intuitive mappings between different sensory dimensions). The colour to sound algorithm is based on the transformation of RGB to CIE LUV colour space and then to sound following a map. White will sound as 3520 Hz pure tone, grey as 100–3200 Hz noise, black as 110 Hz pure tone, red as /u/ vowel sound, green as /i/ vowel sound, blue as 262, 311 and 392 Hz tones (C minor chord) and yellow as 1047, 1319 and 1568 Hz tones (C major chords). The intensity of colours is represented as loudness. However, higher pitched notes have their loudness equalised. [25]

Colorophone

The Colorophone system[1] is a comprehensive research project begun by researchers from NTNU in Trondheim. The main goal of a Colorophone system "is to develop an affordable visual sensory substitution device" [26]. The Colorophone system consists of the Colorophone glasses, the Colorophone smartphone application and a unique colour sonification method. However, researchers intend to create a solution compatible with other sensory substitution methods as vOICe or eyeMusic. The Colorophone system is not only the sensory substitution device, smartphone application and colour sonification method but also multidisciplinary cooperation between researches from different academic institutions around the world.

SoundView

SoundView is a portable auditory guide system with mini-CCD camera, a digital signal processing unit and an earphone. SoundView detects objects tagged with barcodes and lets the user retrieve information about the type, motion and location of the object. The device is using linguistic voice [11].

[1] https://www.colorophone.com/

EyeMusic

EyeMusic is a visual-to-auditory SSD device targeted to the blinds; it provides information about the colour and shape of objects. The sonification method used in this project is based on the musical notes from the pentatonic scale, which has the timbre of instruments. Red is represented as reggae organs, green as rapman's reed organ, white is a choir, blue is a brass instrument and yellow is represented as string instruments [15].

Eyeborg

Eyeborg is an unusual SSD as it is also a live art installation. The tool is personalised for Neil Harbisson, who has achromatopsia. Therefore the device is only analysing the hue and saturation. The Eyeborg is playing sounds through the occipital bone stimulating the inner ear (sound can be heard through bones, for example, conductors are using bone conduction for hearing the sound of a tuning fork; usually the tuning fork will be touching the elbow). The Eyeborg is letting to distinguish 360 hues form colour wheel as well as infrared and ultraviolet [4].

ColEnViSon

ColEnViSon is a colour based image-audio system; the algorithm used in the solution creates a colour map dictionary. To represent sounds, ColEnViSon is using different musical instruments which are playing at the same time independently (polyphony). The choice of instruments is subjective: white is represented as an instrument called music box, red as electric jazz guitar, yellow as synth drum, brown as guitar fret noise, orange as birds tweet, green as shamisen, blue as vibraphone, violet as glockenspiel, black as guitar harmonics and grey as celesta. The algorithm used is reading an image as a column then scanning through it to represent single pixel colour intensity as musical instrument notes. Lighter intensities are higher notes (notes with higher pitch) [14].

2.2.2 Conclusions

Sensory Substitution Devices and Sensory Substitution Software (SSS) have many common points however they differ in the use of colour spaces (HSL, HSV, CIE LUV, RGB, RGBWY etc.), in the aim of the device or software (colour recognition, object recognition, localisation etc.) or the choice of sonification methods. The sonification methods are not unified; they are often a subjective choice operated by the SSD or SSS author or are justified by psychophysical research in cross-modal correspondences. However, the development of new technologies can help to update existing knowledge and allow better and more accurate psychophysical studies (see chapter 2.3).

2.3 Research in cross-modal correspondences

Cross-modal correspondences are intuitive mappings between different sensory dimensions [25], [27]. These mappings can occur between colours, sounds, shapes, height, texture, phonemes, smells, tastes, pain, personalities, touch, temperatures etc. [27]. According to [28] modal correspondences might influence the development of synaesthesia and cross-modal correspondences might share the same tendencies of synaesthesia. Synaesthetic experience occurs when the exposition to one stimulus evokes an experience not associated with that stimulus [29]. It has been found that non-synesthetic subjects can show consistent cross-modal associations between intervals, chords and colours as well as individual instrument timbres and colours [27]. That is why some researchers are stating that auditory stimulation might be well suited for transferring visual information [28]. One of the first well-known example of colour to sound mapping is a scale by Isaac Newton dating back to 1704 where the prismatic spectrum was divided into seven chromatic areas as an analogy to the seven notes of the musical octave [6]. Figure 2 introduces examples of different scales developed by scientists, painters and musicians, these scales are developed subjectively and are not based on cross-modal correspondences, but rather on synaesthetic experiences.

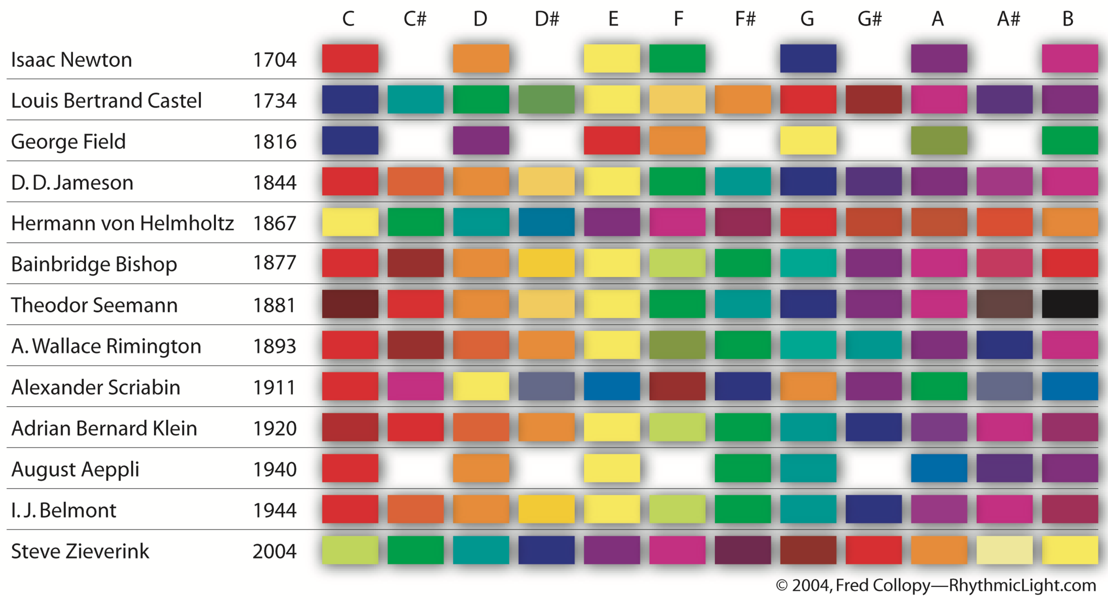


Figure 2: Artificaly created and synesthetic based colour to sound mappings (scales) Source: [30]

Example of modern artificialy created scales are the Haribsson's Sonochromatic Music Scale (see Figure 3) and the Haribsson's Pure Sonochromatic Music Scale (see Figure 4). The first scale is based on equal temperament system, however the pitches and colours are only informative and this scale consists also a microtones [4].

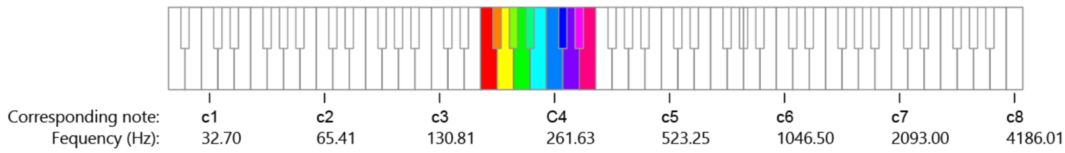


Figure 3: Haribsson's Sonochromatic Music Scale (2003)

The second scale is inspired by the visible spectrum and the transpositions of light frequencies to sound frequencies. This scale is overstepping the limits of human perception as it allows to experience ultrviolet and infrared light [4].

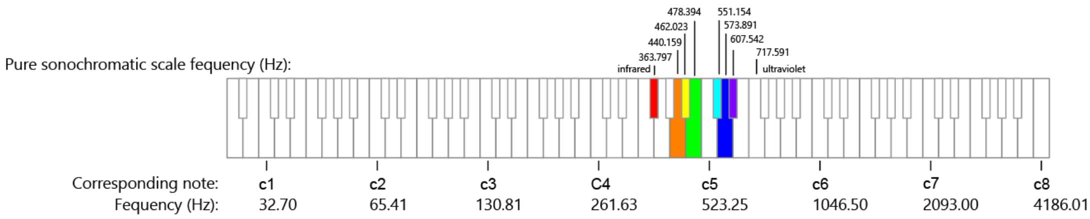


Figure 4: Haribsson's Pure Sonochromatic Music Scale (2005). Please note that keys colored are the closest to the frequency from Pure Sonochromatic Music Scale.

2.3.1 Scales based on psychophysical studies

Creation of a well-established colour sonification method based on cross-modal correspondences requires study of previous psychophysical research. Timothy L. Hubbard found a correlation between lighter visual stimuli and higher pitches, darker visual stimuli and lower pitches, as well as a dependency between music interval distance and the choice of visual lightness (large distance cause more extreme choices), lighter stimuli for ascending melodic interval and darker for descending melodic interval [31]. Research made by Lawrence E. Marks on synaesthesia in perception and language suggest that both may derivate from the same source - phenomenological similarity [32], he found that brightness is expressed as greater loudness and as higher pitch and vice versa [32]. Two studies have been analysed to understand the course of research in cross-modal correspondences. The first research (see 2.3.1 is characterised by the use of simple formula (it uses predefined colour swatches and sound with its' natural loudness) and a large number of participants. The second research 2.3.1 is characterised by a higher complexity in the variables related to the research setting such as colour spaces (use of CIE LUV, CIE LCH and focus on luminance) and sound spectrum (analysing simple waves - fundamental frequency or influences of other formants in vowels).

First research

Amount of participants: 71,
Sounds: eight sine wave tones (32.7, 65.4, 130.81, 261.63, 523.25, 1046.5, 2093.0, 4186.0 Hz)
Sound range: 8 octaves (C1 through C8)
Colours: black, red, green, yellow, orange, violet, and blue
Research focuse: hue - tone
Technology: Microsoft Visual Basic 6.0

The study, introduced by Darcee L. Datteri and Jeffrey N. Howard, examines color associations between eight sine wave tones (32.7, 65.4, 130.81, 261.63, 523.25, 1046.5, 2093.0, and 4186.0 Hz [C1 through C8]) and seven colors presented on colored boxes (black, red, green, yellow, orange, violet, and blue). The sounds natural energy/amplitude as well as the colours' "perceived brightness" were notnormalised. The sound samples lasted for three seconds and were presented ten times each (in total eighty times) through stereo headphones. The colours were presented as coloured boxes in a row in following order black, red, green, yellow, orange, purple, and blue, the order of colours was randomly determined. Seventy-one participants took part in the study; they were instructed to choose the colour subjectively, selecting the "best fit". The researchers found that the associations produced by the participants could indicate an inverse wavelength correlation (e.g. participants were associating sounds with short wavelength to colours with long wavelength). Researchers also suggest that sound to colour associations are consistent and stable. The research was implemented with the use of Microsoft Visual Basic 6.0. [33] This study is interesting for a large number of participants and verified sound to colour associations for a wide range of octaves (eight). However, participants had to pick the sound to colour association from a list of predefined colour swatches, which could have introduced bias the results of the study. Nevertheless, the scale developed by Darcee L. Datteri and Jeffrey N. Howard has found its application in SSD developed by [13].

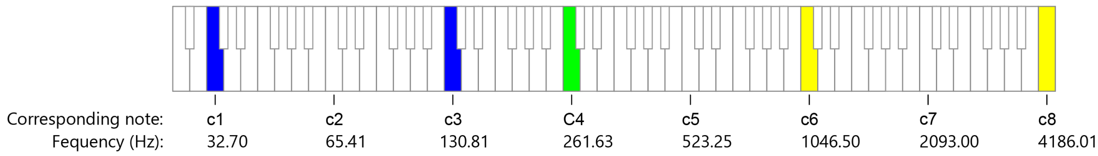


Figure 5: Sound to colour associations from Darcee L. Datteri and Jeffrey N. Howard research

Second Research

Amount of participants: 44,
Sounds: pure tones (100-3200Hz, 440-880Hz)
Sound range: 6 octaves (100-3200Hz), 1 octave (440-880Hz)
Colours: colour picker
Research focuse: hue, saturation - tone
Technology: Matlab (The Mathworks, Inc.) with Psychophysics Toolbox extensions

This is an analysis of an experiment found in the chapter "Effects of Pitch, Noise, and Formant Structure on Associations to Equiluminant Colours". This research aims to reproduce a previously formulated hypothesis about pitch-hue and loudness-saturation relations. Researchers used three sound contexts (6 octaves (100-3200Hz), one octave (440-880Hz) and vocal sounds), the generated sounds were pure tones (pure sound waves, fundamental frequencies) [28]. The amplitude of sounds from six octaves sound context was normalised according to ISO recommendations with following values 100Hz (.92 amp), 200Hz (.68 amp), 400Hz (.52 amp), 800Hz (.4 amp), 1600Hz (.4 amp) and 3200Hz (.3 amp). The sounds from the one-octave context (440, 493, 523, 587, 659, 698, 784 and 880Hz) were not normalised because of the close location.

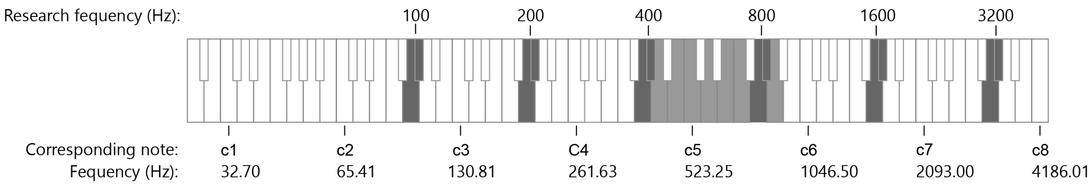


Figure 6: Frequencies used in Hamilton-Fletcher experiment. Dark gray: six octaves sound context: 100, 200, 400, 800, 1600 and 3200Hz (the closest notes from equal temperament system). Gray: one octave sound context: 440, 493, 523, 587, 659, 698, 784 and 880Hz

The study was prepared using Matlab (The Mathworks, Inc.) with and the Psychophysics Toolbox extensions. The instructions were displayed as white text on a grey background with 60% luminance (in CIE LCH colour space). The "best felt matched" colours were picked from a colour circle with a luminance of 65%, saturation 20% and random hue angle. Participants could change the value of saturation (form 0 to 70%) and hue (from 0 to 360) in increments of 5.

Participants could not change the luminance. The time given to the participants were unlimited; they could re-listen to the sounds; each study session usually lasted at least fifteen minutes. The display monitor was viewed through a one-metre black tunnel. The stimuli were presented in random order while the final selected colour was saved as a CIE LCH space value. The results were analysed with ANOVA while CIE U* (red-green) and V* (yellow-blue) and namely "saturation" (CIE LC H's chroma dimension) were dependents variables. Three main findings came from this research: increasing pure tone frequency results into increased yellow-saturation; increasing loudness is results in an increase of saturation; loudness-equalised sounds will also result in a saturation increase as the frequency increases. As a result of his study, Hamilton-Fletcher proposed a sonification method based on cross-modal correspondences which represent white as 3520Hz pure tone, grey as noise between 100-3200Hz with separate frequencies such as 100, 200, 400, 800, 1600 and 3200Hz. Black is associated with 110Hz, red as vowel /u/ and green as vowel /i/; blue is represented as a chord C Minor with frequencies 262, 311 and 392Hz and yellow as C Major chord 1047, 1319 and 1568Hz. The proposed sonification method is illustrated in Figure 7. The average central frequencies values for the vowels were taken from [34]. Hamilton-Fletcher [28] is also pointing to methodological flaws such as ignoring the influences of luminance, lack of use of colour corrected screens; he also recommends analysing the results with CIE LUV or Lab colour space.

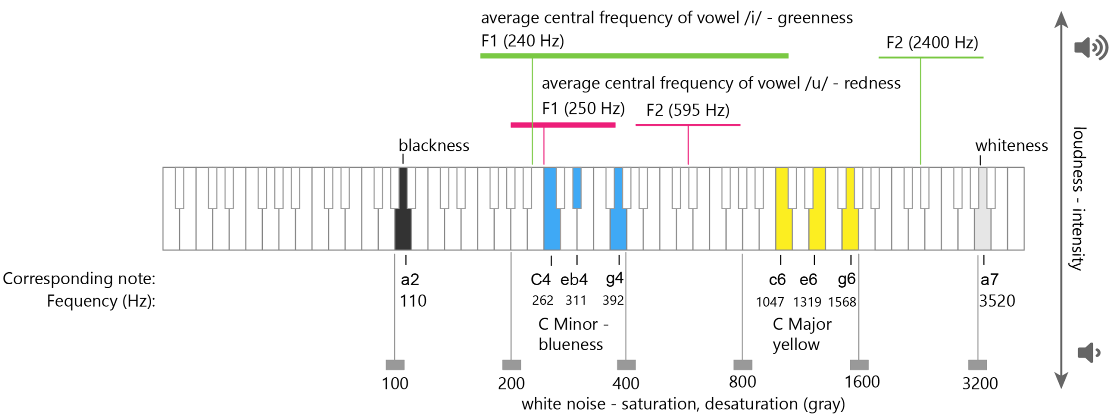


Figure 7: Sonification method proposed by Hamilton-Fletcher

2.3.2 Conclusions

The analysis of psychophysiological studies and sonification methods in sensory sonification devices and software allowed the creation of a list of technological requirements (see chapter 3). Independently from the sonification method that will be chosen, researchers should also consider the influences of hearing loss, tinnitus and cognitive load.

Hearing loss

Hearing loss can be described as a the "*reduced sensitivity for pure tones and problems in the understanding of speech*" [35]. Hearing sensitivity (or loss) is measured with a fixed series of frequencies between 125 Hz and 8kHZ. Hearing loss is often compensated with the use of sign language or cochlear implants. A side effect of hearing loss is a tinnitus or hyperacusis (unusual hypersensitivity or discomfort induced by exposure to sound) [35].

Tinnitus

Tinnitus is experienced by about 10-15% of adults. Tinnitus is not generated in the ear, but by the brain as a response to a hearing loss, a hearing loss affecting the perception of low-frequency can result in low pitched tinnitus, for a loss of high frequency the resulting tinnitus is high-pitched (ringing or hissing sound). The missing sound could be perceived in one ear, both of them or inside the head, and it can be interpreted as phantom sensation [35].

High frequency loss

According to [36] high-frequency hearing loss starts to be noticeable around the age of fifty. One of the reasons for high-frequency hearing loss is the use of mobile phones. Velayutham, P. et al. highlighted a significant difference between high-frequency hearing loss in the dominant ear (used with the mobile phone) and non-dominant ear. For 63% of participants, the dominant ear was the left, 22% reported to use the right ear, and 15% did not have a preference [37]. Figure 8 shows frequency loss through different age groups and gender. According to Figure 8 males above their 40 and woman above their 50 are more likely to experience hearing loss.

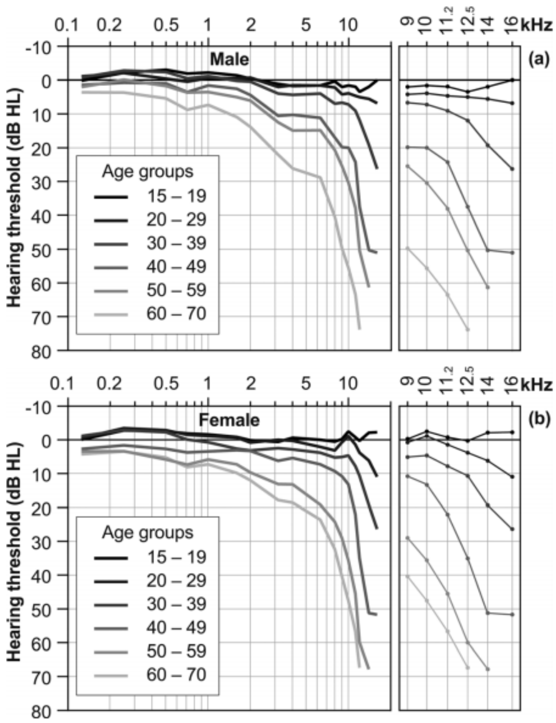


Figure 8: "*Average pure-tone audiograms in dB HL in (a) men and (b) women grouped by their age in decades (the parameter is age group in years). The extended high-frequency range is zoomed for clarity.*" [38] Image retrieved from: [38]

Hearing loss, tinnitus and other hearing loss conditions might influence the use of sonification method or SSD. Hearing loss might mask mapped colour when expressed by a pure tone. Tinnitus might cause false colour recognition if a colour property is mapped to a similar frequency. Studies of the influences of hearing loss and tinnitus on the use of sonification method are needed to understand the related effects and risks.

Cognitive load

"*Cognitive load refers to the amount of working memory load imposed on the human cognitive capacity when performing a particular task*" [39]. Cognitive load is described as limited capacity working memory [40] or amount of mental resources [41]. Measuring cognitive load could help with the optimisation of the mental performance [40], designing an optimal interaction in order to produce the highest task performance [39]. It applies to the mental processes of learning, memory and problem-solving [39]. There are three types of cognitive load: intrinsic, extraneous and germane. The *intrinsic cognitive load* is determined by an interaction between the nature of the material being learned and the expertise of the learners [42], in other words, it represents the inherent difficulty associated with any problem [39] or the effort of absorbing that new information [41]. The *extraneous cognitive load* is under the control of instructional, and it tells about how the information is presented to the learners [39]. The *germane cognitive load* is telling about the processing, construction and automation of schemata [39]. Cognitive load can be defined as subjective load measure (for example subjective assessment of cognitive load NASA-TLX used in research with blind people [43]), combination measure and objective load measures (measuring pupillary response with eye tracker [44]) [39]. Cognitive load is closely related to Kahneman's model of divided attention [45]. The designer, in this case of sonification method or SSD, should aim into minimising the cognitive load by providing only relevant information which will not slow the user down, one of way to assuring that is, for example, to build on existing mental models [41].

3 Methods

3.1 Psychophysiological research design comparison

3.1.1 Laboratory Approach

Researchers Semmelmann and Weigelt [46] describe the standard laboratory approach as a "*cognitive experiment, a participant is presented with a display of different conditions and reacts to this display via a keypress*". Typical laboratory experiment begins with the recruitment of participants, bringing them to the laboratory, to take advantage of a room specifically set up for experimental studies (testing chamber) and then briefing the participants on the research procedure and conditions. Such conditions allow the researcher to control the hardware, the software and the environment. According to Semmelmann and Weigelt [46] laboratory experiments are demanding in therm of resources, time and often rely on participants from the local student population, something that might limit the validity of the study.

Sound presentation

Laboratory research involving auditory stimuli do often rely on headphones. According to [47] headphones can help a participant to focus on the sound stimuli by covering the ear and isolating from noise sources as well as reducing the environmental effects thanks to the short distance between eardrum and transducer. Another advantage of headphones is the separation of signals between two ears (for binaural tests).

3.1.2 Virtual Reality

Virtual Reality (VR) "*integrates real-time computer graphics, body tracking sensors, audio/visual/touch displays, and sensory input devices to immerse a participant in an interactive computer-generated virtual environment (VE) that changes naturally with head and body motion*" [48]. VR seems to be well suited for different types of studies involving humans. Many researchers see three-dimensional (3D) stimulus presentations as a unique advantage [48], [49] which allows behavioural and performance tracking [48], in other words it allows the control of many confounding variables [50] as 3D stimulus can be precisely configured [48]. Pugnetti et al. [51] highlights that what makes VR so special is that stimulus becomes an integral part of a virtual environment. The potential of the VR is in the authentic visual and auditory representation of reality [50]. Pugnetti et al. [51] suggests that VR might be the preferable tool to develop assistive devices or control hands-free interactions. According to Schoeffler et al.[50] VR has two most common types of cave automatic virtual environments (CAVEs) and head-mounted displays (HMDs). With CAVEs VR, the user wears stereoscopic glasses and observes images as they are projected on walls, sometimes also floor and ceiling of a room. The researcher highlight that, while the advantage of CAVE is a very wide field of view, this comes with the tradeoff requiring special equipment and space. HMDs can be monocular or binocular, when worn over the head they provide a wide field of view without the need for a wide space or additional resources [50].

In the experiment made by [52], the participants were supposed to asses the appearance of light and colours. The results show difficulties in the estimation of the size of both the desktop room and the room in the Immersive Projection Technology (ITP) system where projection was displayed on five walls without a ceiling. The researchers also found that comparison of real and virtual rooms exposed unsatisfying differences in shadowing and colour appearance [52]. Researchers Wilson and Soranzo [49] suggests that in spite of the high level of immersion in VR the stimulus might not evoke a "realistic" psychological response.

3.1.3 Web-based research

According to [46] laboratory data acquisition in psychophysics can be complemented or substituted by online studies. Semmelmann and Weigelt [46] state that online studies can answer one of the main research methodology questions: "*To what extent can the results of a single study be mapped to the whole population?*". Online research can also support replication, confirmation and generalization of previous studies as well as asking new questions. Many researchers noticed the advantages of web-based research such as enabling large scale of studies [46], [47], fast data gathering, accessibility and efficiency [47] and quick pilot studies. Data gathering through the Internet is sometimes called crowdsourcing [47]. Leeuw [53] explains that complex experiments in a Web browser are possible thanks to the recent increase of sophistication of Web technologies. Semmelmann and Weigelt [46] mentioned that participation in the study from home comes with an inevitable environmental variability. The surroundings can vary in noise levels, lights and unwanted distractions, hardware variability (computers or screens) and software installed on the machine. However, Leeuw [54] noticed that studies requiring tight control of the visual stimulus presentation and response recording could be significantly affected by confounds. Disadvantages of web-based researcher are widely described by Birnbaum [55] who discusses the problem of self-selection which can make the research not generalizable to a larger population, the influences of the input device on participant response and the issue of multiple submissions. Some of the researchers are concerned that web-based studies have reduced internal validity. Still, reduced internal validity could be balanced by increased external validity. This problem was investigated by [56] who concluded that the internal validity of web-based study might be not necessarily lower than lab experiments. The researchers argue false discovery effects in a web-based study might be troublesome due to noise data. Though, there is no greater danger of it than in lab-based studies. Researchers prepared recommendations for web-based studies to avoid common pitfalls.

Recommendations

Honing and Ladinig [57] prepared a set of recommendations for web-based research. One of the first problems they discuss is **serious and non-serious responses**. No-serious responses (or non-serious participants) are those who do not complete the experiment, do not provide all the required information or take part in the experiment too quickly or hastily. To verify the seriousness of the participant Honing and Ladinig advises consistency checks and time logging. Another problem of web-based studies are **dropouts**, Honing and Ladinig suggest the following structure:

- Technical check.

- Biographical questions (increase involvement).
- Instructions.
- The study itself (no longer than fifteen minutes).
- Value for the participants (e.g. feedback about the results or research context).
- Follow up questions about future participation (which could also indicate seriousness).

The missing element in the recommendations from Honing and Ladinig is to gather feedback regarding the research; if kept as an open question it might result in interesting comments helpful in recognising research pitfalls.

Web based research

A common procedure in web-based research is to have it as part of a three-phase study [58]:

- Standard laboratory experiment.
- Laboratory experiment using a web application.
- Online experiment, delivered through the Internet.

Semmelmann and Weigelt [46] define this structure as the classical "lab", "web-in-lab", "web" sequence. This setup allows the researchers to isolate the influences of technology and the environment. A comparison study ran by [59] registered the perceived contrast, it was found that the mean ratings of the observers were not significantly different. Nevertheless, studies regarding contrast not taking place in a controlled environment can be considerably diverse than those run in a laboratory condition. Another example of web-based study is research made by [60] a field study regarding colour consensus and focal colour, they gathered data from over seven hundred participants as mapped CIELAB hues and lightness for basic colours. The results were consistent with previous studies. Another comparison study ran by [61] about colour contrast and readability concluded that web studies lead to the same results as laboratory experiments. Other researchers [62] which studied assessment of luminous environment found that data collected in the laboratory and online do not have statistically significant differences; their findings suggest that to remove bias the amount of participant should be more than one hundred. Still, the amount of the online experiments could be increased by growing the number of tools supporting for web-based experiments, an example of open source tool is jsPsych[1] [53], [54]. Other example of web-based tool for psychometric image evaluation is QuickEval[2] [63].

3.2 Web-based solution features

Most of the reviewed studies (regarding either cross-modal correspondences of colour and sound or sonification methods and sensory substitution devices and software) are laboratory-based experiments (for example [22], [16], [23], [12], [13], [24], [26], [11], [15], [14], [64]). It should, therefore, be of interest to understand how a web-based solution could be implemented to extend and support the results of laboratory data. This part of the thesis explores web-browser technologies to understand how they can fulfil the requirements of a psychophysiological experiment in sound and colour on the web. For the scope of this project, the requirements are based on the literature review (see chapter 2).

[1]https://www.jspsych.org/
[2]https://www.ansatt.hig.no/mariusp/quick/

Colour fetaures

- A non-biasing colour picker.
- Support of HSL (Hue Saturation Lightness colour representations system).
- A neutral grey background.

Sound features

- Ability to reproduce white, pink and brown noise.
- Ability to reproduce pure tones.
- Ability to reproduce multiple pure tones at the same time.
- Ability to control the loudness of the pure tones independently.
- Ability to pan sounds (left, center, right).
- Ability to reproduce sounds with a natural timbre.
- Ability to reproduce vowels.
- Ability to control the sound length.
- Ability to control loudness and to normalise the sounds.
- Ability to define a sound range slider interface.
- Ability to create random clusters.

Measuring confounds

- Ability to access the brightness settings of the user's monitor and its specifications.
- Ability to measure the user environmental illumination through a webcam or luminance sensor on the device to ensure equiluminant conditions.
- Ability to access screen resolution and orientation.
- Allowing full screen.
- Timekeeping of the various parts of the test: displaying, playing stimuli, submitting the answer.
- Record whether the participant is using speakers or headphones.

3.3 Web application use case

According to the recommendations gathered during the literature review (see chapter Mobile web and Web-based research 3.1.3), the experiment flow should follow the Use Case Diagram in Figure 9. First, the participant should express the will to participate in research and signs the consent form; then it should be presented with a short demographics survey (presented in this sequence to increase the involvement). After the survey, the real experiment can begin with a tutorial session on how to use the application and testing the sound level/ brightness; then the participant is guided through the test session which should be less than fifteen minutes. After the experiment, the participant should be given the chance to comment on the research itself, which might help to find possible pitfalls or improve the research for future iterations. In the end, the results of the individual experiment should be displayed in a comprehensible visual form.

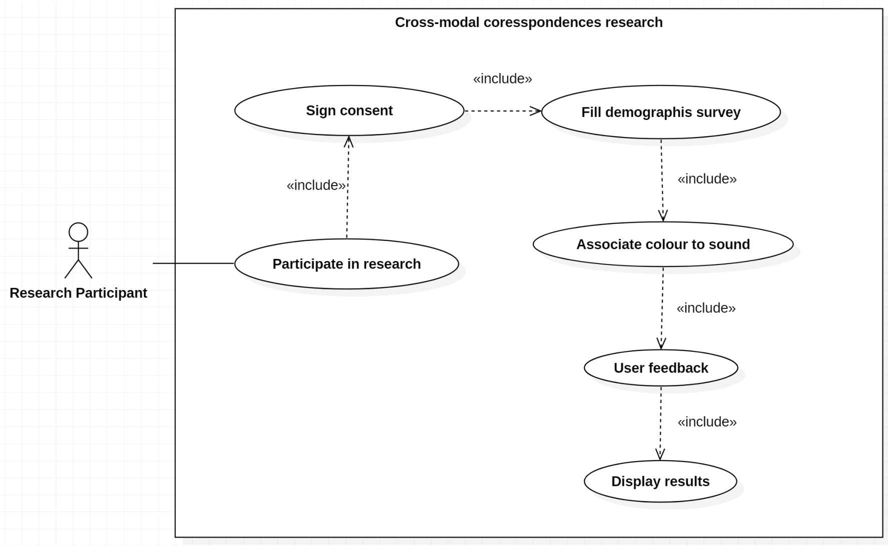


Figure 9: Use case diagram of research in cross-modal correspondences in sound and colour.

3.4 Technology Assessment

Web technologies suitable for research in cross-modal correspondences between colour and sound are discussed in this portion of the thesis. This project has been initiated from the background research and "future work" ideas of three other previous projects: the Advanced Project Work, Colour In Interface Design and Integration Project. For this reason, some of the technologies and frameworks have been explored and analysed in the past by the author. Re elaborating this experience allowed for the definition a robust list of research problems, albeit quite different from what made up the previous projects, and the development of a web application specifically made for research purposes which should lead to significant research contributions. The final implementation is available on GitHub under the address `https://github.com/aniWeyn/colourtosound`

VueJS

VueJS[3] is a progressive framework for building user interfaces. Its main advantage is the high adaptability, which means ease of integration with other libraries or existing projects. VueJS has a strong and large community support [65]. The authors of the VueJS libraries are easy to reach through the official VueJS forum or Discord channel. VueJS is also famous because of its simple and understandable documentation.

Tone.js

Tone.js[4] is a framework based on the Web Audio API which supports the creation and management of interactive sound in the browser in an intuitive way [66].

Customized colour picker

No one of the analysed colour pickers libraries was suitable to use in colour research (as the colour picker should not bias the participants with predefined colours or colour structures) therefore with the use of VueJS a new colour picker was created. Custom sliders were created with the use of the vue-slider-component[5] as this library had the best documentation and allowed for a great length of adjustments.

Firebase Realtime Database

The Firebase Realtime Database[6] is a cloud-hosted NoSQL database. The Firebase Realtime Database is based on a JSON data structure and is suitable for storing complex data and larger applications [67].

Lodash and JSONPath Plus

Lodash[7] is a library which allows convenient operations on arrays, objects, strings and numbers. JSONPath Plus is a library for the extraction of data from JSON files[8]. Use of Lodash and JSONPath Plus could be described as an equivalent of SQL for JavaScript for querying data from Firebase.

3.5 Technology Justification

The research specifications and requirements were crucial elements in the choice of the technologies, frameworks and libraries. VueJS was chosen as the main framework over Angular or React, which are currently bigger market players. Currently VueJS[9] has 139,333 stars on GitHub, Angular[10] has 48,379 stars and React[11] has 129,710 stars. GitHub starts could be an indicator of popularity and trust of the framework among developers. VueJS is most suitable for developing small, flexible web applications or rapid prototyping. Vue files have a straightforward structure which, in the most basic form consists of a template (HTML structure), scripts and styles. VueJS

[3] https://vuejs.org/
[4] https://tonejs.github.io/
[5] https://nightcatsama.github.io/vue-slider-component/
[6] https://firebase.google.com/
[7] https://lodash.com/
[8] https://github.com/s3u/JSONPath
[9] https://github.com/vuejs/vue
[10] https://github.com/angular/angular
[11] https://github.com/facebook/react

has built in many functionalities such as Actions / Events (for example supports on-click or on-move events) which are a timesaver for a developer. The built-in features also help to reduce the amount of code which doesn't focus on the application logic itself. One of the biggest advantages of VueJS is that it can be used in the top of other programming frameworks, which means that it can be combined with Angular or React, that makes components written in VueJS easily reusable. VueJS is also easily reusable because it doesn't require knowledge of TypeScript (as in Angular), which makes it easier and faster to understand for someone who would like to reuse the component. Another advantage of VueJS is the built-in support of The PRPL Pattern[12] (push, render, pre-cache, lazy-load). The PRPL Pattern is an experimental pattern made with a thought about slow mobile networks and fast loading of web applications on mobile phones [68]. Another advantage of VueJS is VueCLI[13] which allows for rapid installation of the required libraries, in this case, Vue Router[14] (which supports route - view mappings) and Vuex[15] used for the management of data between different components (in other words a temporary database in the browser).

Tone.js

Tone.js[16], so far, is the most mature framework among those based on the Web Audio API, it has 8,132 stars on GitHub and is actively developed, Tone.js has the largest API and an excellent documentation with and live code examples, the author of the library is reachable through email and willing to reply to questions. ToneJS API covers most of the sound features mentioned in the Sound features section (see 3.2). Other candidates were the timbre.js[17] library, which unfortunately is no longer developed (960 stars on GitHub, last commit in 2015, lack of responses for issues). Wad[18] is a library that was actively developed between 2014-2016, it has above 1000 GitHub stars, it is still actively developed but not with high frequency, however, this library is lacking good documentation and live examples of use. Pizzicato.js is also an actively developed library[19], it is well documented and has live examples, however the scope of the library seems to be smaller than Tone.js. Pizzicato.js is more focused on the creation and manipulation of sounds, timbre and articulation (as the name of library is indicating), the library has many open issues and barely 877 stars on GitHub.

Colourpicker

In a colour perception research, the colour picker is an important part of the research design, the distribution of colours on the colour picker might introduce bias and influence the results of the research. Therefore a customised colour picker had to be developed for this project. There are many good libraries to chose from such as Vue-color[20] or the previously used Bootstrap Colorpicker[21], however, they are not suitable for this research purposes (see Figure 10). The colour picker designed for this research is a simple square shaped div containing three range

[12]https://developers.google.com/web/fundamentals/performance/prpl-pattern/
[13]https://cli.vuejs.org/
[14]https://router.vuejs.org/
[15]https://vuex.vuejs.org/
[16]https://github.com/Tonejs/Tone.js
[17]https://github.com/mohayonao/timbre.js
[18]https://github.com/rserota/wad
[19]https://github.com/alemangui/pizzicato
[20]https://github.com/xiaokaike/vue-color
[21]https://github.com/farbelous/bootstrap-colorpicker

slider, one for each of the three HSL parameters. Since a range slider vue-slider-component was used, it allowed for high customisation of the range sliders and the support of mobile phone browsers.

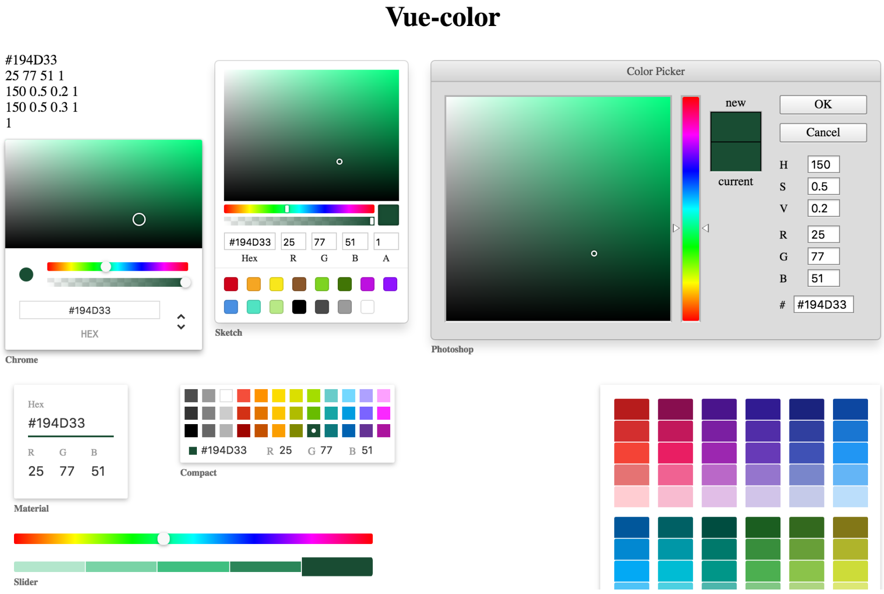


Figure 10: Example of variety of colour pickers in Vue-color library. Source: [2].

Bootstrap and Sass

For managing the visual layer Bootstrap v4.3.1[22] was chosen in conjunction with a Sass compiler, Sass-loader[23] for global managing of the colour variables across the entire project. Bootstrap is a set of prepared and reusable visual elements which helps to keep the design of the project clear and consistent. This project benefits from Bootstraps' layout grid system (which helps whit the placement of the elements on the website), utilities such as flex (which allows evening more exact element placement) and the pre-prepared and user accepted components (such as the behaviour of buttons on-focus and on-hover). Another suitable technologies which could easily replace Bootstrap is CSS Grid Layout[24], Flexbox[25] or a framework such as Zurb Foundation[26]. Nevertheless, the visual identity of a web application for this project should be neutral and non-invasive.

Firebase

Firebase seems to be a lighter solution than Relational Databases. Firebase, in contrast to traditional databases, allows to insert JSON file as a source of data and dynamically change the Firebase data structure with incoming JSON. In Firebase, the data is stored as a list with nodes;

[22]https://getbootstrap.com/docs/4.3/getting-started/introduction/
[23]https://github.com/webpack-contrib/sass-loader
[24]https://developer.mozilla.org/en-US/docs/Web/CSS/CSS_Grid_Layout
[25]https://developer.mozilla.org/en-US/docs/Learn/CSS/CSS_layout/Flexbox
[26]https://foundation.zurb.com/

the insertion of new data reminds of the push function of a traditional array. Firebase, with limitations, is free of charge, and it is well suitable for small projects.

Lodash and JSONPath Plus

To improve the code readability and simplify working with the arrays and objects, a Lodash library was used.

3.6 Tone.js - Sound Features

Tone.js is capable of fullfilling sound features reqirements gathered from literature review. Tone.js is able to reproduce white, pink and brown noise[27], reproduce pure tones[28] and multiple pure tones at the same time with ability to control the loudness of the pure tones independently and creation of random clusters[29], ability to pan sounds[30] reproduce sounds with a natural timbre can be achieved through additional library[31], control the sound length[32], control loudness and to normalise the sounds[33]. The reproduction of vowels need to be further investigates as vowels are dependent on frequencies (formants), Tone,js allows to adjust frequencies so it might be possible to reproduce vowels.

3.7 Web API Measuring Confounding Variables

The access to users' screen brightness through a Web API is unfortunately deprecated[34]. The measure of participants' environmental illumination on the device to ensure equiluminant will be possible in the future through light sensor[35], the access to screen resolution is possible[36], as well the access to screen orientation is possible on most of the browsers [37], the access to full screen is partially supported[38], the time keeping can be achieved with JavaScript function Date.now()[39], record whether the participant is using speakers or headphones[40] is possible however requires recognition of type of device as it recognize as it display all audio input and video input deices such as microphones, cameras, headphones and speakers.

3.8 Prototyping

Prototyping is an important phase of development. In this case, it was important to create a simple, minimalistic, non-invasive design for the colour picker. Figure 11 introduces the design of the colour picker, which consists of two non-intrusive range-sliders and an area to display the chosen colour.

[27] https://tonejs.github.io/docs/r13/Noise
[28] https://tonejs.github.io/docs/r13/Oscillator
[29] https://tonejs.github.io/docs/r13/PolySynth
[30] https://tonejs.github.io/docs/r13/PanVol
[31] https://github.com/nbrosowsky/tonejs-instruments
[32] https://tonejs.github.io/docs/r13/Time
[33] https://tonejs.github.io/docs/r13/Volume
[34] https://developer.mozilla.org/en-US/docs/Web/API/Screen/mozBrightness
[35] https://developer.mozilla.org/en-US/docs/Web/API/DeviceLightEvent/Using_light_sensors
[36] https://developer.mozilla.org/en-US/docs/Web/API/Screen
[37] https://developer.mozilla.org/en-US/docs/Web/API/Screen/orientation
[38] https://developer.mozilla.org/en-US/docs/Web/API/Element/requestFullScreen
[39] https://developer.mozilla.org/en-US/docs/Web/JavaScript/Reference/Global_Objects/Date/now
[40] https://developer.mozilla.org/en-US/docs/Web/API/MediaDevices/enumerateDevices

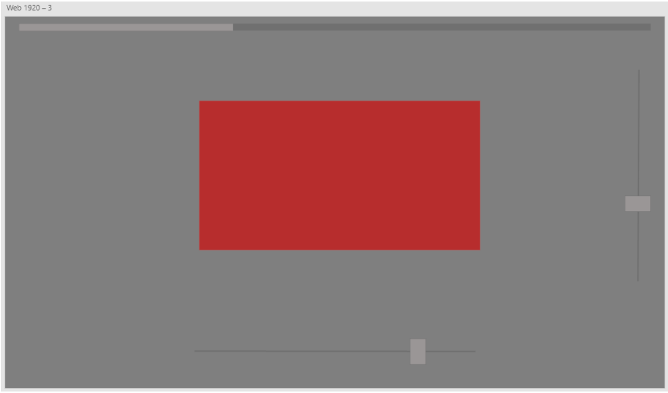


Figure 11: Prototype of colour picker

3.9 Designing cross-modal associations experiment

The experiment was designed based on analysis made in literature review (see Chapter 2). The experiment consist of seven parts:

1. Consent form
2. Survey
3. Instructions
4. Sound to colour associations mapping
5. Colour to sound associations mapping
6. Participant feedback
7. Displaying participants' results

Consent form

The consent form has been prepared according to NSD – Norsk senter for forskningsdata[41] guidelines. The consent form used in the study is available in Appendix A.1.

Survey

To keep the experiment short, three (of four) essential questions about music experience, colour experience and synesthetic experience were adapted from the survey used by Griscom [27]. The data is evaluated with the use of a Likert scale [69] to let the participants easily express their experience, to avoid misleading answers, all questions include the "No opinion" option. Survey questions are attached in Appendix A.2.

Instructions

Instructions are in text form and describe the interactive elements. The instructions of the experiment disappear as the participant starts the experiment. A random sound is played during the instructions to show how the interface works, and the answer is not saved in Firebase.

[41] https://nsd.no/personvernombud/en/help/information_consent/

Sound to colour associations mapping

In the sound to colour association experiment, the participants have to match a colour to sound they hear. To choose the colour, the participants have to use the HSL range slider. The range slider always starts in HSL(0%, 0%, 50%) to avoid suggesting the colour to the participant. The sound (sine wave frequency) is played upon opening the page and is also available through the play button. The sounds are divided according to music octaves (a whole tone scale starting from C2 to B2, C3-B3, C4-B4, C5-B5, C6-B6), one note is chosen at random from every octave, two notes are chosen from the C4-B4 octave, in total six notes. All six notes are repeated three times, for a total of eighteen samples. One note from the chosen notes is randomly chosen to be played during the instructions. As previous studies always referred to one note chosen by the researcher from a selection of octaves (see Chapter 2.3.1) it was decided to propose a new way of mapping colour to sounds. In this research, all the participants receive random notes from the chosen octaves, and then their results are compared across the octaves. In this way, the results are not dependent to and generalised from single notes in an octave, but the colour associations are mapped to a wider range of sounds. The time required to complete the experiment is measured, as well as the time spend on mapping, and overall time spend on part one and part two of the experiment.

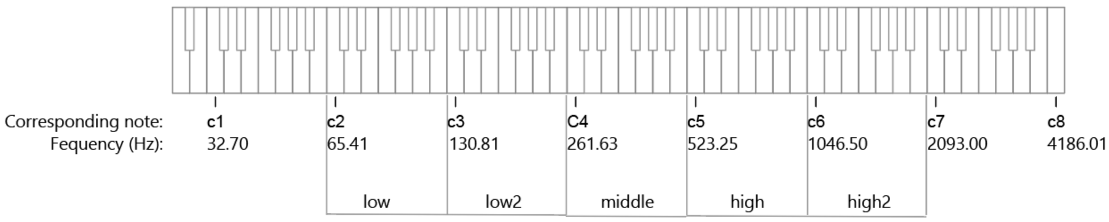


Figure 12: Range of sounds used in the experiment from the chosen octaves (low, low2, middle, high, high2 (as named in the JSON file) one note was picked at random, two notes were randomly picked from the middle octave. The notes were restricted to the whole tone scale, starting from C.

Colour to sound associations mapping

In contrast with the first part of the experiment, in the colour association experiment, the participants have to match a sound to the colour they see on display. This part aims to discover how consistent the participant's answers are. The displayed colours are the colours chosen by the participant for the perceived sounds in the first part of the experiment. Six additional colours are added (such as yellow, red, green, blue, black and white) to make the research more comparable with previous studies, discover differences in correlations between lightness, saturation within the same hue and to try to discover correlations between colour properties such as vividness. The additional colours appear in four shades with different level of saturation and lightness. The values of the additional colours are available in Appendix A.5.

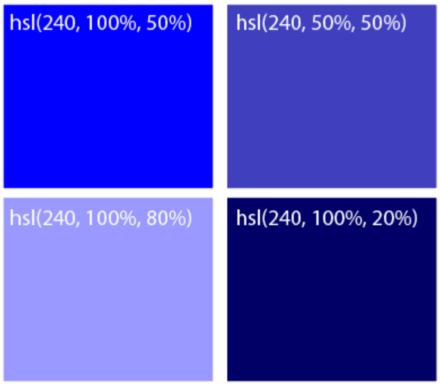


Figure 13: Example of additional colours added to the research.

Participant feedback

In the post-experiment survey the participants are asked about their perceived length of the study, technical issues (were they able to hear all sounds), the brightness of the screen, the device used during the study and how the sounds were played (speakers, headphones etc.). Then the participants are asked about hearing loss and tinnitus. At the end of the survey, the participants can provide feedback in a text input area. Moreover, the participant's answers can be compared with data gathered through the Web API such as screen width, height, colour depth and pixel depth, available screen height and width. The participant's answers and all the gathered data should help to improve future research, understand how the participants are taking part in the study (what is the natural environment and behaviour of the participants).

Displaying participants' results

At the end of the study, all participant responses are displayed as simple colour boxes with the associated sound label. The colour boxes are playing associated sound on click.

4 Implementation

4.1 Application overview

The following application was implemented with the scope of establishing whether the web technologies are mature enough to carry out psychophysiological research in cross-modal correspondences between sounds and colour. The code of the application is available in a GitHub repository: https://github.com/aniWeyn/colourtosound and live at: https://aniweyn.github.io/colourtosound/.

4.2 Application features

The cross-modal mappings experiment application is built in Vue.js. The components responsible for the consent form, surveys, experiments, progress bars, feedbacks and results are separate and have been built with the idea of being reusable. These child components are nested in parent components. Therefore it is easy to understand which components are used during the study and in which order.

Consent form

The consent form is loaded from a JSON file and displayed in an application through conditional rendering. The JSON file can be easily replaced if the application will be reused in another research.

Survey

The survey component is independent from the data. However, the survey data are stored in an Array Object; the Array Object has a JSON structure and can be replaced with a JSON file. Therefore it can be easily placed in other projects. All answers are sent to Firebase as they are submitted. The overview of the survey components is in Figure 14.

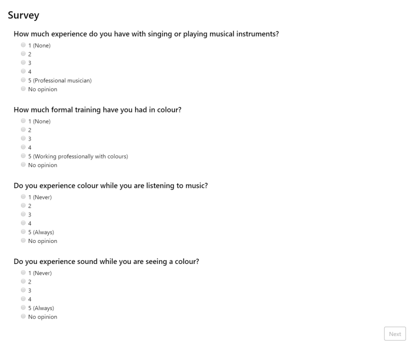


Figure 14: Survey component.

Instructions

Instructions are displayed above the interactive elements as HTML objects. Showing and hiding the instructions is achieved through conditional rendering. The state of the instructions is stored in Vuex Store and change through mutations. The instructions and sound to colour experiment components are presented in Figure 15.

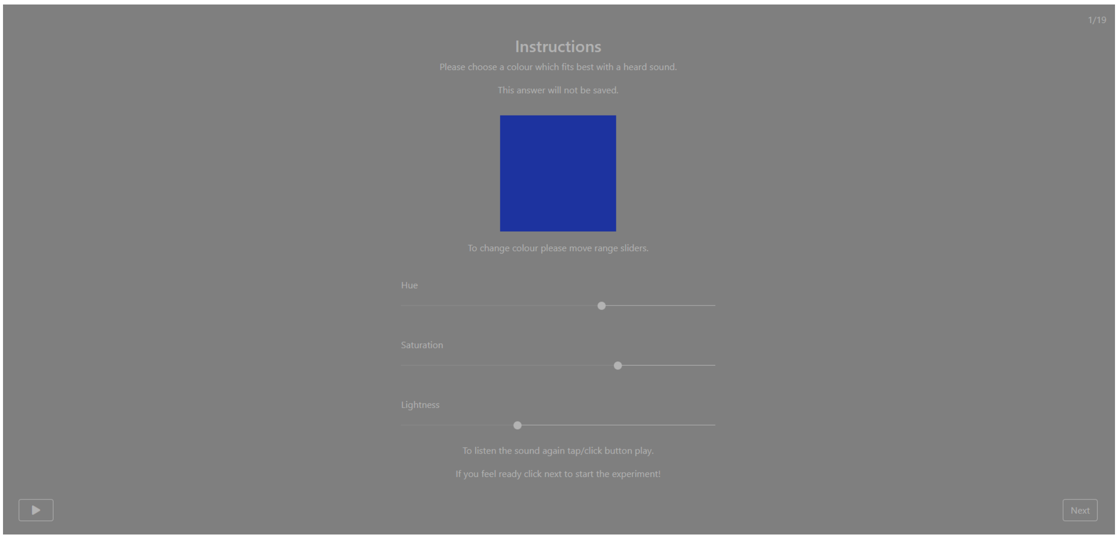


Figure 15: The instructions and sound to colour experiment components. Browser view.

Sound to colour associations mapping

The sound to colour experiment is based on two separate components:

- The colour picker component, responsible for displaying a coloured square and three range sliders which are representing hue, lightness and saturation.
- The tone component, responsible for playing sounds and for the logic of advancing between the trials of the experiment, updating Vuex store mutations and sending data to Firebase.
- The progress bar component which displays the participant progress.

The experiment logic is initialized in the parent component to ensure components independence from the data. The data is randomized and shuffled in the parent component and then accessible through Vuex store. The Colour picker component uses a two-way data binding model and reacts on @change events. Two-way data binding allows to receive the data from user input and automatically updates the chosen element or data object. The tone component updates the Firebase Real-time Database after each click on the "Next" button with the participant's data. To distinguish between the participants and control for multiple attempts, the participants are signed in anonymously in the database (see Figure 17). The data is divided for the different parts of the study. The participant's answers are not only stored in Firebase but also saved to temporary Vuex stores to be later retrieved from the Sound picker component and Results component. The buttons Play and Next are intentionally placed far away from each other to avoid accidental submissions. Furthermore, the button Next is disabled until one of the range sliders is moved at least once. The Progressbar component is placed in the top right corner to show participant progress in study discreetly. The progress bar also helps to avoid dropouts from the study by informing how much trials are left. The range slider dot was programmed to changed size to adapt to different screen sizes thanks to a CSS media query. Therefore the dot has a size of 30 x 30 px on smaller devices. The components are presented in Figure 16.

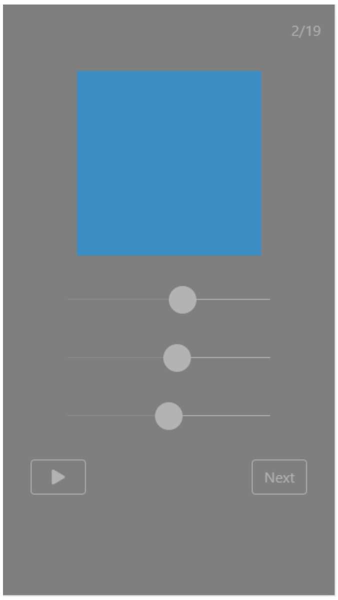


Figure 16: Colour picker used in sound to colour experiment. Mobile view.

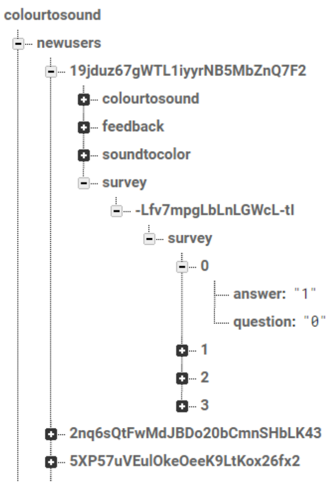


Figure 17: Firebase data structure. Example of annonymous user and its' attempt.

Colour to sound associations mapping

The colour to sound experiment is based on the Soundpicker componen (see Figure 18. In this component, the range slider is used to select from an array of notes. On @change event the note name is sent to a method which triggers the sound of the note. The colours displayed to the participants are retrieved from Vuex store then concatenated with the predefined colours: yellow, red, green, blue, black and white thanks to the Lodash library, and then shuffled.

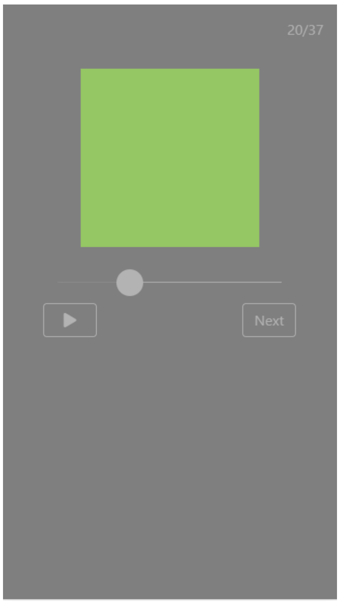


Figure 18: Sound picker used in colour to sound experiment. Mobile view.

Participant feedback

The Feedback component is built similarly to the ConsentForm component and the Survey component with the exception that its parts are gathering data about the user screen width, height and colour depth. Also, the data about the overall time spent on the experiment, and its particular parts are sent as feedback to Firebase. The view of the Feedback component is attached in Appendix A.4 in Figure 42.

Results

The Results component displays the participant's answers and lets them hear how they associated colour and sound (see Figure 19).

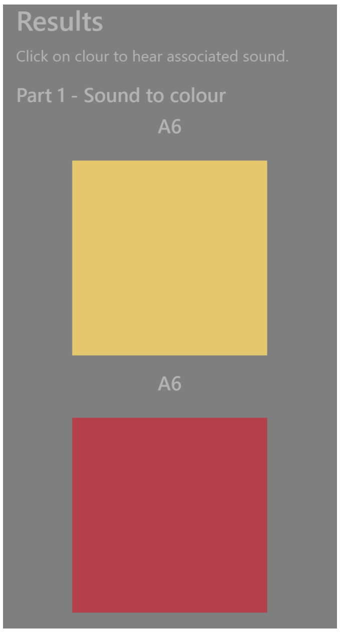


Figure 19: Results component. Mobile view.

Charts

The Charts, in contrast to the previous components, is implemented as a separate view which is available on a separate page from the experiment itself. The routing to another view is implemented with the use of the Vue Router library, which simulates traditional redirection. The charts are generated through the Highcharts[1] library. The data displayed through Highcharts are queried with JSONPath Plus library, an example of query looks as follows:
"*$.newusers[*].survey[*].survey[0].answer*", next the data are chunked through Lodashs' *countBy* function. From the received Object, the key and value are distinguished, next the data are prepared as data series and provided to Highchart. The data are read from a JSON file, exported from Firebase. However, the structure of the file is the same as in Firebase which leaves which means that it would be possible to connect the Charts view with Firebase and change the charts from static to dynamical, reacting to changes from the database. The generated charts are available at the address: `https://aniweyn.github.io/colourtosound/#/charts` and are used in the Experiment Results 5 and Results 6 chapter; the charts not used in the mentioned chapters are listed in Appendix A.7.

[1] https://www.highcharts.com/

5 Experiment Results

5.1 Participants

Invites to the experiment were distributed through social media. Most of the participants are students or alumni of NTNU in Gjøvik. The total number of participants which took at least part in the survey and the first part of the experiment is forty-five. The number of participants which took part in all parts of the research (survey, sound to colour part, colour to sound part and feedback) is thirty-five. The number of participants which took part only in the survey and the sound to colour part is seven and three participants took part in the survey, colour to sound part and feedback (this is a result of unknown bug). Only the data of participants who took part in all parts were analyzed. The participants used their personal devices and were free to choose when to do the test during the day. Participants were asked to turn off applications that might affect the screen colour response such as those reducing "blue-light". The use of a laptop over a smartphone or headphones over speakers was up to the participants.

5.2 Findings

The findings provide an interesting input, as both significant and in line with what found by previous studies. Figure 25 introduces the distribution of notes assigned to colour such as red, yellow, green, blue. The notes are collected into six octaves and represented on the chart as octaves (whole tone scale from C2 to B2, C3-B3, C4-B4, C5-B5, C6-B6, see Chapter 3.9, section Sound to colour associations mapping). The lines are drawn based on the number of samples. Figure 25 shows that blue was most often chosen to match sounds from the third octave, green for sounds from the fifth octave and yellow for the sixth octave. Colours red and yellow are chosen more often through all octaves while blue has a prominent peak in the third octave as green has it in the fourth octave. Figure 21 shows the distribution of the different notes associated to black and white; it can be seen that for black most of the associated notes are from the second octave and for white, there is notable a peak in the fifth and sixth octaves. It is important to notice that this distribution is based on the defined colours, (see Chapter 3.9) section Colour to sound associations mapping and Appendix A.5 for the colours values).

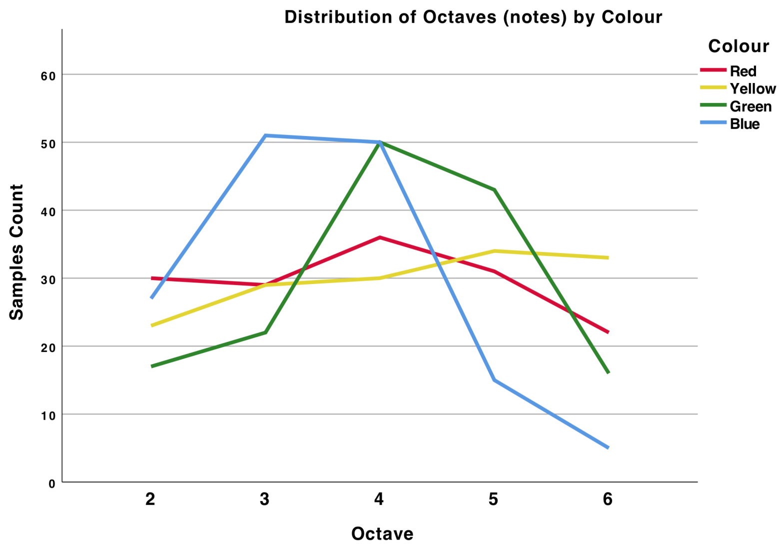


Figure 20: Distribution of notes among red, yellow green and blue. Colour to sound.

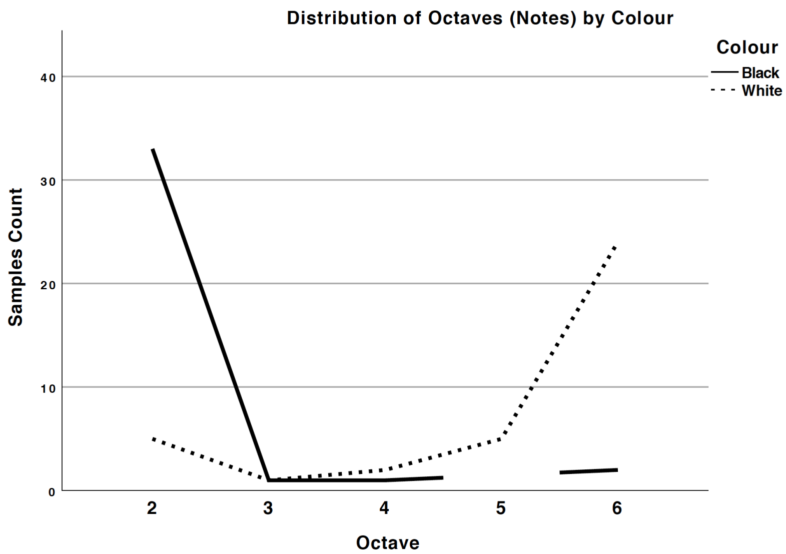


Figure 21: Distribution of notes among black and white. Colour to sound.

The data from the sound to colour study and colour to sound for additional colours study were analyzed against the Spearman's rank-order correlations, which is a nonparametric version of the Pearson correlation. "*Spearman's correlation coefficient [..] measures the strength and di-*

rection of the association between two ranked variables" [70]. In this part the results of sound to colour experiment are presented. Figure 22 indicates that there is a significant correlation between the octave and the colour lightness as well as between the octave and colour saturation. Figure 23 introduces mean HSL value for octaves, where an increase of mean value for lightness and saturation can be observed.

Correlations

			Hue	Lightness	Saturation	Octave
Spearman's rho	Hue	Correlation Coefficient	1.000	.047	.250**	-.012
		Sig. (2-tailed)	.	.207	.000	.751
		N	718	718	717	718
	Lightness	Correlation Coefficient	.047	1.000	.188**	.531**
		Sig. (2-tailed)	.207	.	.000	.000
		N	718	718	717	718
	Saturation	Correlation Coefficient	.250**	.188**	1.000	.317**
		Sig. (2-tailed)	.000	.000	.	.000
		N	717	717	717	717
	Octave	Correlation Coefficient	-.012	.531**	.317**	1.000
		Sig. (2-tailed)	.751	.000	.000	.
		N	718	718	717	718

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 22: The Spearman's rank-order correlation for non parametric data. Sound to colour.

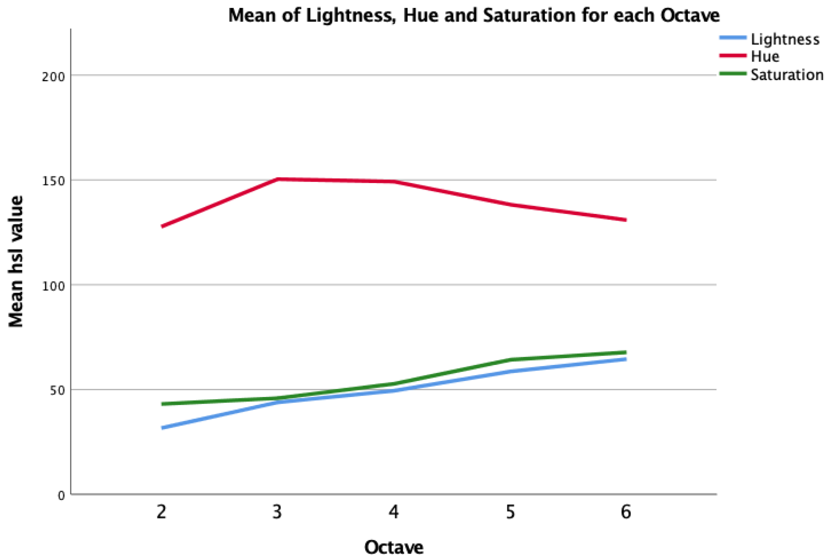


Figure 23: Mean values of lightness, hue and saturation for each octave.

This part discuss the results of Spearman's rank-order correlation against colour to sound experiment for red, green, blue, yellow, black and white. If black and withe are exlcuded the relation with the octave becomes significant for lightness and hue (negative correlation) (see Figure 24). When black and white are included in the analisis the relation with the octave is significant for saturation and lightness (see Figure 25). Figure 26 shows correlations for all che colours chosen by the participants. The correlation is significant between octaves / saturation, and octaves / lightness.

Correlations

			Saturation	Lightness	Octave	Hue
Spearman's rho	Saturation	Correlation Coefficient	1.000	.000	.036	.000
		Sig. (2-tailed)	.	1.000	.385	.992
		N	593	593	593	593
	Lightness	Correlation Coefficient	.000	1.000	.397**	.000
		Sig. (2-tailed)	1.000	.	.000	1.000
		N	593	593	593	593
	Octave	Correlation Coefficient	.036	.397**	1.000	-.122**
		Sig. (2-tailed)	.385	.000	.	.003
		N	593	593	593	593
	Hue	Correlation Coefficient	.000	.000	-.122**	1.000
		Sig. (2-tailed)	.992	1.000	.003	.
		N	593	593	593	593

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 24: The Spearman's rank-order correlation for non parametric data. Colour to sound experiment part. Defined colours without black and white colour.

Correlations

			Saturation	Lightness	Octave	Hue
Spearman's rho	Saturation	Correlation Coefficient	1.000	.260**	.197**	.110**
		Sig. (2-tailed)	.	.000	.000	.004
		N	667	667	667	667
	Lightness	Correlation Coefficient	.260**	1.000	.487**	.000
		Sig. (2-tailed)	.000	.	.000	1.000
		N	667	667	667	667
	Octave	Correlation Coefficient	.197**	.487**	1.000	-.067
		Sig. (2-tailed)	.000	.000	.	.085
		N	667	667	667	667
	Hue	Correlation Coefficient	.110**	.000	-.067	1.000
		Sig. (2-tailed)	.004	1.000	.085	.
		N	667	667	667	667

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 25: The Spearman's rank-order correlation for non parametric data. Colour to sound experiment part. Defined colours with black and white colour.

Correlations

			Hue	Saturation	Lightness	Octave
Spearman's rho	Hue	Correlation Coefficient	1.000	.036	.011	-.023
		Sig. (2-tailed)	.	.115	.613	.298
		N	1964	1964	1964	1964
	Saturation	Correlation Coefficient	.036	1.000	.222**	.235**
		Sig. (2-tailed)	.115	.	.000	.000
		N	1964	1964	1964	1964
	Lightness	Correlation Coefficient	.011	.222**	1.000	.498**
		Sig. (2-tailed)	.613	.000	.	.000
		N	1964	1964	1964	1964
	Octave	Correlation Coefficient	-.023	.235**	.498**	1.000
		Sig. (2-tailed)	.298	.000	.000	.
		N	1964	1964	1964	1964

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 26: The Spearman's rank-order correlation for non parametric data. Colour to sound experiment part. Results for colours matched by participants in sound to colour and defined colours from colour to sound experiment.

The results concerning the web-based solution and user experience are discussed in Chapter Results 6.

6 Results: web based research evaluation

6.1 Web based experiment

The web-based experiment was not only designed to test the cross-modal correspondences but also to evaluate possibilities of web-based research to keep track over confounds in comparison to strict laboratory controlled studies. One way to compare web-based research to controlled laboratory studies is to measure confounds. In the web-based study, the confounds cannot be controlled. However, some of them can be measured. The charts discussed in this section are also available at `https://aniweyn.github.io/colourtosound/#/charts`. Table 1 shows overview through defined confounds and ability of developer to implement them into web solution (see Chapter 3.7). Most of the features are available or partially available through Web API.

Feature:	**Web API support:**
Access the brightness settings of the user's monitor and its specifications	No
Measure the user environmental illumination through a webcam or luminance sensor on the device to ensure equiluminant conditions	Partially supported
Access screen resolution	Yes
Access screen orientation	Yes
Allowing full screen	Partially supported
Timekeeping of the various parts of the test: displaying, playing stimuli, submitting the answer	Yes
Record whether the participant is using speakers or headphones	Partially supported

Table 1: Evaluation of measuring confounds based on Mozzila Web API documentation.

Participants screen resolutions were verified through a Web API (see Figure 28a and Figure 28b) and through a post-experiment survey where participants were asked what type of device were they using (see Figure 27). Ten participants answered "smartphone" and twenty-seven selected the answer "personal computer" while the data gathered from Web API indicates that ten of the measured heights are below 768 px, where devices which have height equal or above 768 px could be considered as tablets or small personal computers (for example iPad height is 768 px).

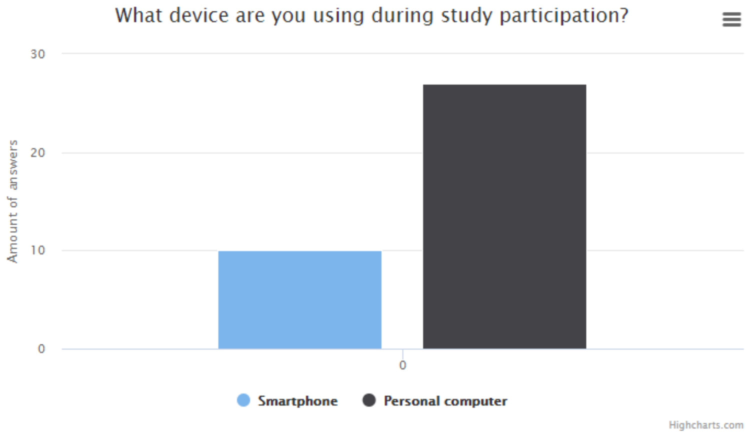
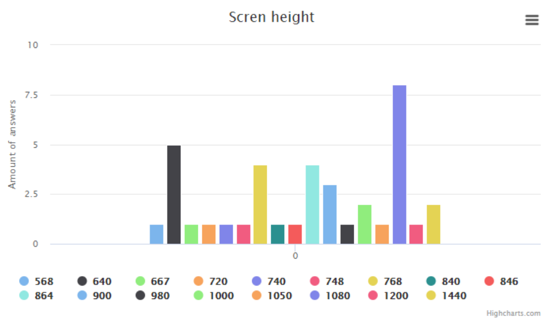
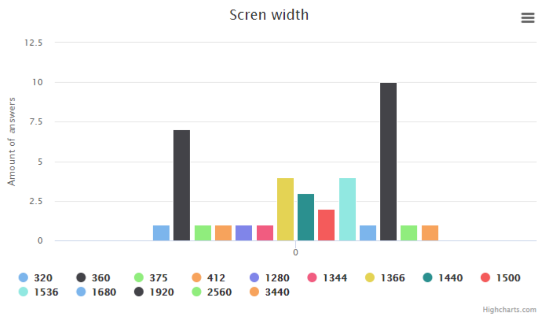


Figure 27: Devices



(a) Screen height



(b) Screen width

Figure 28: Width and height gathered through Web API

The participant's session duration was measured for the sound to colour experiment, the colour to sound experiment and the overall time between the start of the sound to colour experiment and sending the response of feedback (see Figure 30). The average session duration for the sound to colour part was around seven minutes, for the colour to sound part it was around five minutes and the total time spend for both parts of the experiment and feedback were around 15 minutes (see Figure 30 and Figure 32). Participants were also asked to match the perceived length of the study to a Likert scale (from 1 to 5, with the additional "No opinion" answer), for six participants the study was too long, thirteen participants chosen answer with number 4, for fourteen participants the study had neutral length, two participants perceived study as short, three participants did not express their opinion.

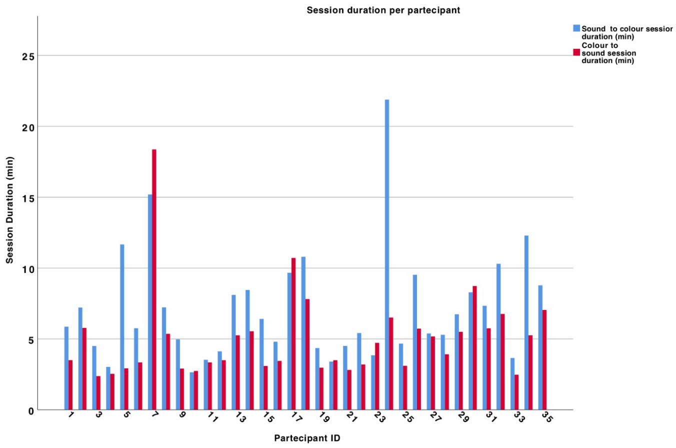


Figure 29: Session duration per participant for sound to colour and colour to sound experiment.

	Sound to colour session duration (min)	Colour to sound session duration (min)	Total experiment duration (min)
Mean	7.13134	5.02002	15.41373
N	35	35	35
Std. Deviation	3.909092	3.037694	7.421574
Minimum	2.645	2.381	7.630
Maximum	21.883	18.371	37.649
Median	5.86322	3.91902	14.59053

Figure 30: Mean, N, Std. deviation, minimum, maximum and median of sessions duration.

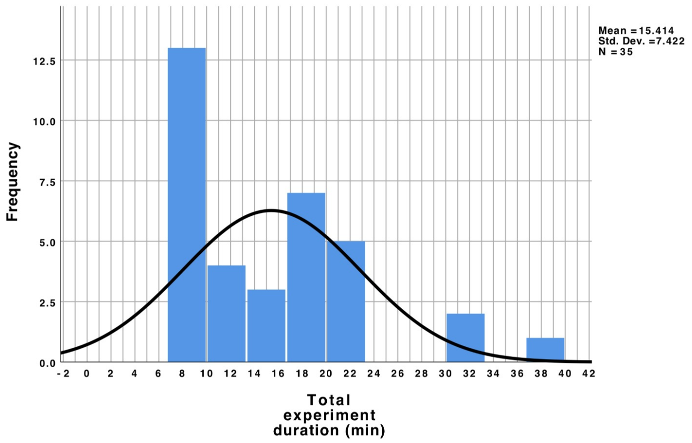
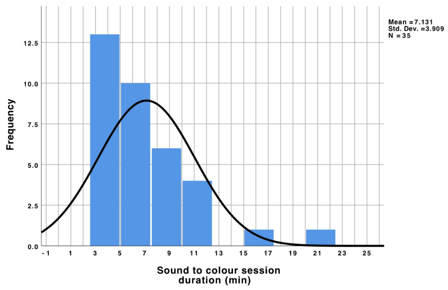
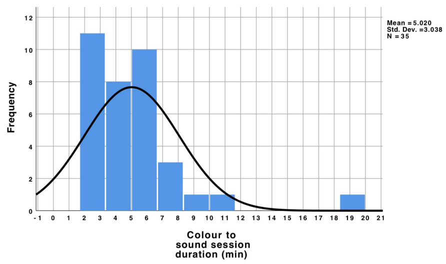


Figure 31: Total session duration (min).



(a) Colour to sound session duration (min)



(b) Sount to colour session duration (min)

Figure 32: Measured time during experiment.

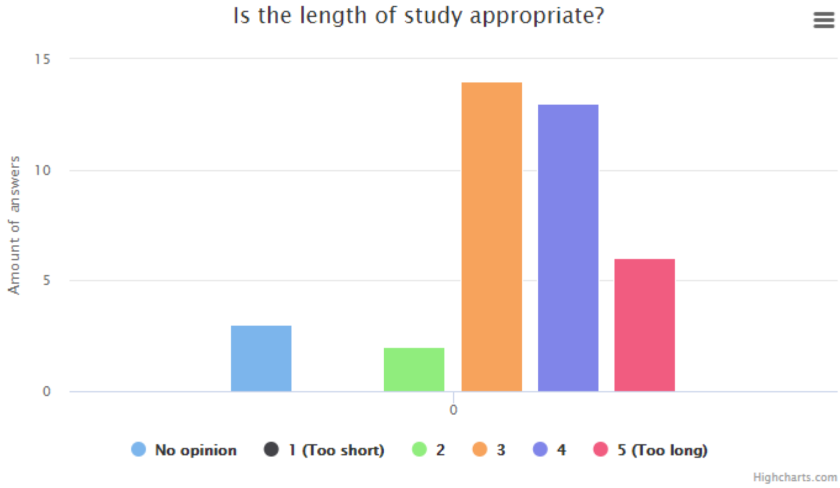


Figure 33: Length of study.

The experiment set up also allows learning about the natural environment of the participants in the post-experiment survey. The participants were asked two questions about the device which played sounds during the experiment and the brightness of the screen, according to the participant's subjective experience. Seventeen participants used an external device to participate in the study; three used external speakers and seventeen used headphones (see Figure 34). Thirteen participants reported a medium screen brightness, sixteen selected the option four (bright) and seven selected very bright, two participants perceived their screen brightness as dark, one participant selected the "I don't know" answer 35. In addition the screen colour depth was measured, most of the participants (thirty-six) had 24px colour depth while two participants had 32px colour depth (see Figure 36).

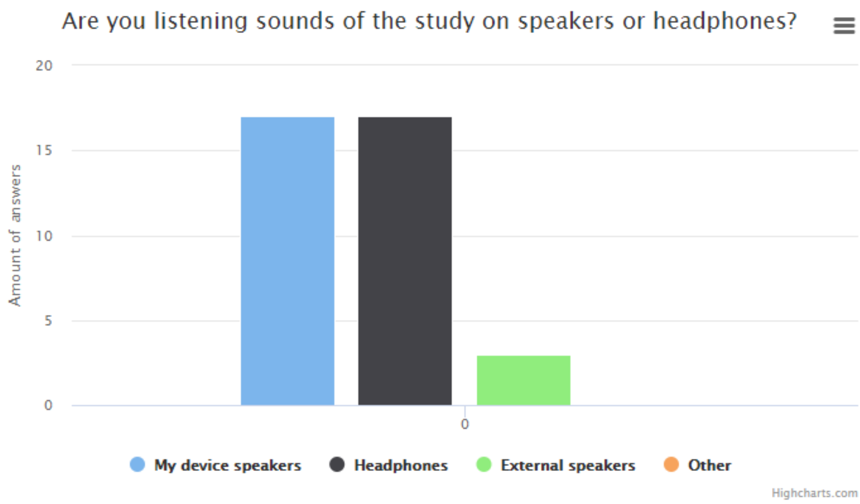


Figure 34: Headphones.

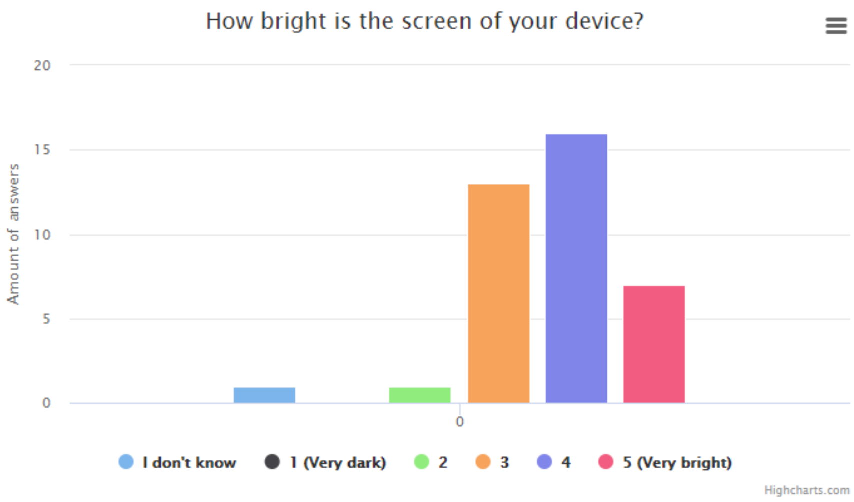


Figure 35: Brightness.

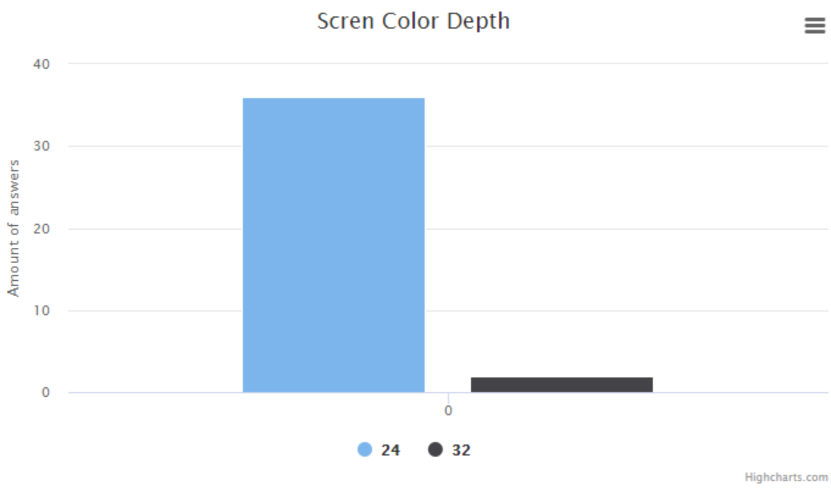


Figure 36: Screen colour depth

6.2 Sounds features

The above Table 2 shows an overview of the sound features which might be used by researchers who would like to study sound to colour cross-modal correspondences and its possibility to be implemented in Tone.js (see Chapter 3.6).

Feature:	Tone.js support:
Reproduce white, pink and brown noise	Yes
Reproduce pure tones	Yes
Reproduce multiple pure tones at the same time.	Yes
Control the loudness of the pure tones independently	Yes
Pan sounds to left, center, right	Yes
Reproduce sounds with a natural timbre	Yes
Reproduce vowels	Need further investigation
Control the sound length	Yes
Control loudness and to normalise the sounds	Yes
Create random cluster	Yes

Table 2: Sound features.

Participants were also asked about their ability to hear all the sounds during the study. The majority (thirty) answered that they were able to hear all sounds, two participants selected number four, three participants selected number three, one participant selected number two and two participants did not express their opinion (see Figure 37).

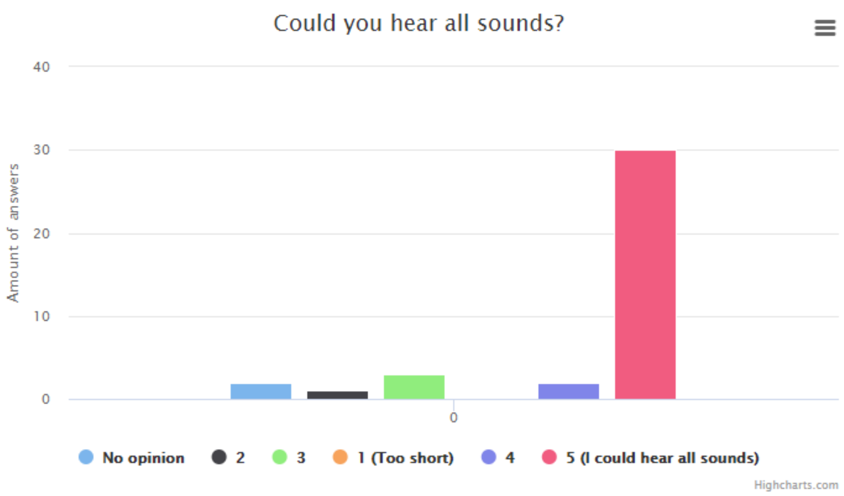


Figure 37: Heard all sounds.

As mentioned in Chapter 2.3.2, potential consumers of SDD might suffer from hearing losses, tinnitus and high-frequency losses. During the study, the participants were asked about their hearing conditions. Two participants selected that they might suffer from hearing loss, twenty-two participants believe that they do not suffer from hearing losses and eleven participants checked their state with a doctor, and they do not have any hearing losses (see Figure 38). However, when asked about tinnitus they selected seven times the answer "Yes", seven times "I might" and twenty-three times "No" (See Figure 39). As mentioned in Chapter 2.3.2 tinnitus might be a consequence of reduced hearing sensitivity. Therefore the five participants who selected answer "No" regarding hearing loss might actually suffer from hearing loss but not being aware of it.

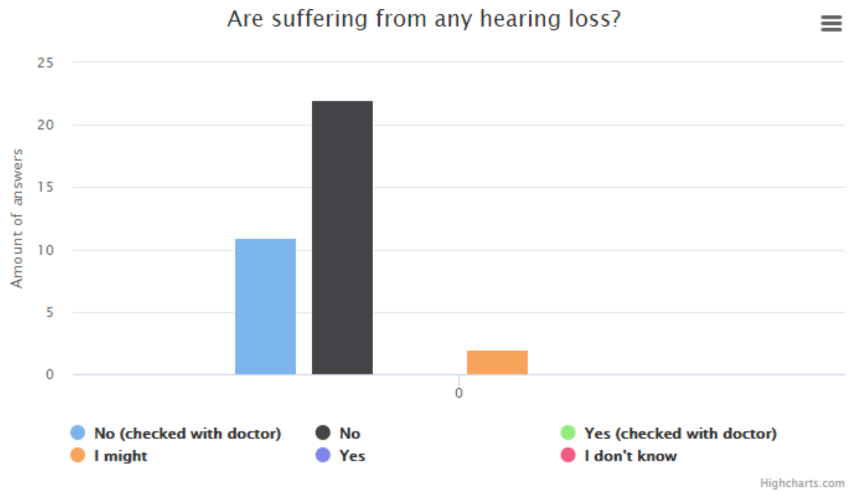


Figure 38: Hearing Loss.

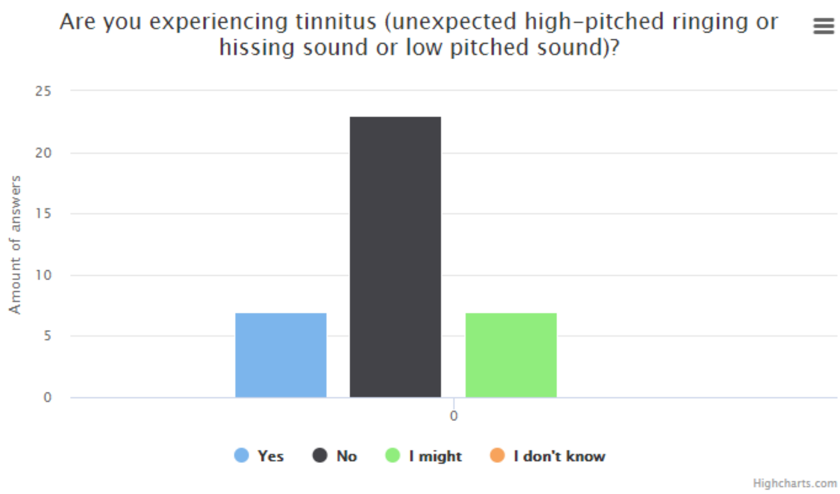


Figure 39: Tinnitus.

7 Discussion

Based on the results of the study, web-based research should have a role in studies regarding cross-modal correspondences between colour and sound. The results are in line what reported by previous laboratory studies confirming that the confounding variables related to the use of web-based research have a limited effect on the outcomes.

7.1 Colour sonification

Interpretation of results

The experiment results illustrate the colour-sound and sound-colour relations. In particular the tie between sound and saturation as well as sounds and lightness. When considering only RGBY colours correlation was significant also between lightness-sounds and hue-sounds (negative correlation). When also considering black and white RGBYWB colours, significant relations were also found between saturation-sounds and lightness-sounds. Analysing the sound to colour experiment results, which includes colours freely chosen by the participants as well as a list of predefined colours ("all colours") the lightness-sound and saturation-sound relations were found to be significant.

Table 3 shows the comparison between correlation for sound-lightness and lightness-sound. When the value of lightness increases the sound frequency value rises too. The lightness-sound correlation is the strongest among all other correlations, which might suggest that sound frequency could be used to represent saturation in a colour sonification method, instead of trying to represent hue through the sound frequency. Further studies in cross-modal correspondences between hue and sound should be carried out to investigate this characteristic.

Experiment	Correlation	Correlation Coefficient
Sounds-colours	sound-lightness	.531
RGBY colours-sounds	lightness-sound	.397
RGBYWB colours-sounds	lightness-sound	.487
All colours-sounds	lightness-sound	.498

Table 3: Correlations between lightness-sound and sound-lightness.

Experiment	Correlation	Correlation Coefficient
Sounds-colours	sound-saturation	.317
RGBY colours-sounds	saturation-sound	.036
RGBYWB colours-sounds	saturation-sound	.197
All colours-sounds	saturation-sound	.235

Table 4: Correlations between saturation-sound and sound-saturation.

Table 4 presents the values of correlations for sound-saturation and saturation-sound. What is interesting, the correlation is stronger for colours picked by participants (sounds-colours, all colours-sounds) than for predefined colours. This results might indicate further studies in saturation to sound where the saturation could be represented by, for example, noise. Therefore a new study could be carried with a noise variable.

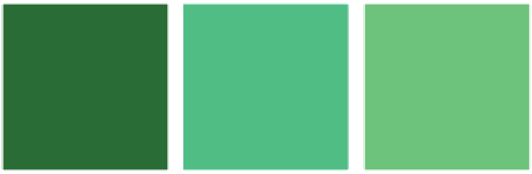


Figure 40: Mean values - colour interpretation for octave 2, 4 and 6 (see Figure 23)

Figure 40 presents the correspondent mean values of lightness, saturation and hue (HSL colour) for each octave. The figure presents three colour swatches which show the mean colour for the second, fourth and sixth octave. It can be seen that as the sound frequency grows, the saturation and lightness are increasing as well. However, the increases and decreases in hue value are perceived as green colour. Figure 41 shows the combined results of the colour distribution of the pre-defined colours form Figure 20 and Figure 21.

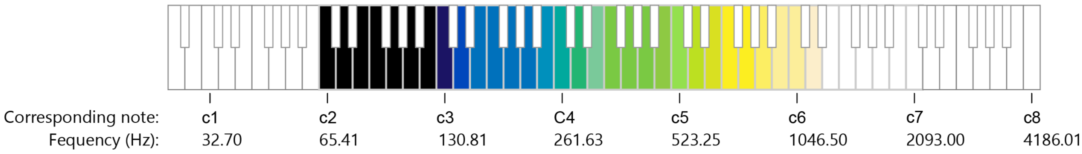


Figure 41: Interpretation of results from Figure 20 and Figure 21. Hue-sound correlation negative correlation with lightness-sound correlation. When sounds frequency increases the value of hue decreases (Figure 20). When lightness increases sound frequency increases (white), when lightness decreases sound frequency decreases (black) (Figure 21).

The colour to sound mapping seems to be more suitable for exposing participants on particular colour properties. Therefore the results seem to be more suitable to begin defining cross-modal correspondences for colour sonification methods. The colour sonification methods should also take into account hearing losses, tinnitus and especially cognitive load (see Chapter 2.3.2). According to the literature review, the effect of hearing loss and tinnitus has not been explored in details.

7.2 Web based experiment

7.2.1 Technology

In the context of colour sonification and sensory substitution devices, all three research approaches are useful. Most of the research done in sonification methods and sensory devices and software are laboratory studies. Hamilton-Fletcher [28] highlights that previous laboratory studies in cross-modal colour to sound correspondences were lacking a strictly scientific approach. The creation of sonification methods might benefit from the application of web-based crowd-sourced studies to support laboratory data, allowing for a higher external validity thanks to a potentially higher number of participants. According to Honing and Ladinig [57] in studies regarding music perception, low internal validity might be a desirable setting, researchers argue that, for a participant, to listening to sound stimuli in the environment where they are usually listening to sound might positively influence the ecological validity of the results. Virtual reality approach seems to be the perfect solution in studies of cross-modal correspondences between colour or sound and shape, height, texture, movement. VR might be the most suitable solution for testing the usability and cognitive load of sonification method before the prototyping phase.

Interpretation of results

The current development of Web API seems to suit well and support web-based psychophysical research. A researcher could develop web-based solutions which could be used in either controlled laboratory conditions as well as field conditions. The results of such " hybrid" study could benefit from a higher external validity as it would use the same mechanism for measuring confounding variables. The Web Audio API and Tone.js framework give a large control over the in-browser sound creation and as the study was carried without sounds issues (see participants response in Figure 37) the Web Audio API and Tone.js framework can be recommended as a reliable tool for psychophysical studies.

User Experience

Researchers who would like to carry out fully non-controlled studies have to prepare their solution for different screen resolution, different input type (such as mouse pointer or touch). However, the responsiveness is well supported by many layout frameworks even though it requires effort to be implemented. The importance of the research participant experience (user experience) in a web-based study became clear during the "proof of concept" research conducted for the Advanced Project Work course (IMT4894) [71]. The comfort and simplicity in the use of a solution and comfort of participation in a research study are defined through the analysis of the feedback gathered during the aforementioned project. The details surrounding the errors in research design and user interface design discovered through the feedback analysis are described in the Advanced Project Work report [71] and appropriate improvements were applied during the development of the current solution. The sound experience might differ between participants as well as the adoption of external speakers and headphones. Therefore it would be advised to investigate what group of sounds can be assumed to sound well independently from the device quality and type. Some devices might have built-in sound normalisation or equalisation so that the perceived volume of the different frequencies might be affected. The study followed the recommendation of Honing and Ladinig [57] and took on average fifteen minutes. However, nineteen participants reported that the study was long or too long, while sixteen judged it as adequate. Therefore in future studies, this time could be reduced to ten minutes (for non-controlled environment studies).

Seriousness

The data gathered through the Web API can confirm the *seriousness* of the participants (see Section 3.1.3). Based on the data gathered during the experiment, it can be said that the seriousness of the research participants was high. In the survey, the participants were asked what kind of devices they were using (see Figure 27), their answers were compared with the data gathered through the Web API ((see Figure 28) such as device height and width to confirm the truthfulness of the participants. Another measure of *seriousness* suggested by Honing and Ladinig [57] is the time spent on the trial questions. Figure 30 and Figure 29 shows that the minimum time spent on the experiment session for the sound to colour and colour to sound parts was less than 3 minutes. A participant with such prompt responses could be categorised after the analysis of her/his answers, as a not serious participant and excluded from the study.

Participants feedback

In the open feedback question, the participants could express their opinions. However, some of them still provided feedback as a private message directly to the research author. The participants were expressing more interest in the colour to sound experiment than in the sound to colour experience. A few participants were surprised that some of the sounds were repeated. Two participants complained about the sound quality and noise from the speakers. A few participants were surprised that the instructions disappeared after the start of the experiment. One participant complained about the placing of the buttons, and that the progress bar was not visible enough. One participant asked about more fun facts about the theory of study at the end of the study. Two participants reported struggling with matching the colours to the sounds and the sound to the colours. Some participant expressed they discovered sound-colours associations which they never noticed before. Overall the study was described as "*interesting*", "*easy to do*", and also as a "*fun and a cool experience*".

Improvements

The project work could be improved by:

- Gathering data about the browser.
- If the participant drops out during the study, a pop-up should open and inquiry on the reason.
- In the post-experiment survey, the participants should be asked about the model they used to associate colour-sound and sound-colour to gather an insight into the participants mental model.
- Encourage to provide feedback after the study.
- Redesigning the sound picker to make it more comfortable to use.
- Analyse the abilities of typical speakers to avoid noises during sound reproduction.
- Improving the page responsiveness to keep the colour patch always in the middle of the screen.
- Increasing the size of touch elements to min 44px, according to the WCAG recommendations[1].

[1] http://w3c.github.io/Mobile-A11y-Extension/#proposed-new-mobile-guideline-guideline-2-5-touch-and-pointer-make-it-e

- Ask the participants about their volume settings and try to measure headphones, speakers volume.

8 Conclusion

This Master Thesis describes web-based psychophysical research, evaluates its advantages, disadvantages, technological solutions and proposes an example of web-based research. This work describes the characteristics of Web APIs and Web Audio APIs and shows their use in web-based research. The proposed research in cross-modal correspondences between sound-colour and colour-sound has produced significant results to prove that web-based research can be used in psychophysical studies as well as that web technologies are mature enough to carry out research studies if the inherited limitations are accounted for. The research in cross-modal correspondences results are in line with previous studies, Chapter 3 describes the research design while Chapter 5 provides a description and data visualisation of the result. Full range piano graphics are used to compare the scales, the results of the research in cross-modal correspondences and the results of the experiment. The full range piano graphics offer reference points such as the symbol of the C note in every octave and the corresponding base wave frequency. The solution implemented during the research is a useful example of a light client-side application, developed with the use of Vue.js and connected to a NoSQL database - Firebase. The implementation is described in Chapter 4 while Chapter 6 evaluates the results of the implementation.

8.1 Contributions

This work is a successful contribution to many disciplines, such as:

Applied Computer Science

. This work is unique as it provides insights into the development of the, growing in popularity, front-end framework - Vue.js. Pre-prepared components (after small adjustments) can be reused on top of other client-side frameworks such as Angular, React or used in combination with a server-side solution. The implementation provides examples of the connection to Firebase, as well as examples of how to query nested JSON files to retrieve data. Another critical characteristic of this report is the discussion regarding Web API, Web Audio API and its framework Tone.js. This work indicates how to solve the requirements of psychophysical research. This thesis is valuable not only because of its applied character but also because of the extensive literature regarding web-based research, its advantages and disadvantages, the evaluation of other researchers recommendation, the implementation of such recommendations and the suggestions of changes to the recommendations. This report also evaluates the overuse of Virtual Reality in cross-modal correspondences research and in which cases it might be a better solution over web-based research or controlled laboratory research. This work also justifies design solutions and user experience recommendations.

Psychophysics

This work contributes to the psychophysics discipline by providing universal examples of implementation psychophysics elements in web-based research.

Cross-modal correspondences in colour and sound, sonification methods and sensory substitution devices and software

This thesis provides a new perspective regarding studies in cross-modal correspondences outside controlled laboratory studies and pushes the research to a natural/ecological environment. This thesis suggests a new method to research cross-modal correspondences by allowing larger freedom of mappings providing to the user a wide range of sounds and a customised colour picker. The thesis also suggests a new method of analysing the mapped sounds by categorising them into octaves. The work is unique as it has carried out sound to colour study and its inverse mapping - colour to sound. The results of the experiment are in line with previous studies which prove that web-based research in this domain is equally valuable. The literature review provides an overview of sensory substitution devices and software, and describers implemented colour sonification-methods, as well as introducing the reader to other colour to sound scales and research in cross-modal correspondences. The work also provides a unique point of reference through the piano graphic, which allows for better visualisation of the research results, which will hopefully inspire other researchers to create similar graphics to describe their results.

8.2 Future Work

The research in cross-modal correspondences is not a young discipline. However, rapid technology development uncovers new possibilities and research directions. Researchers are able to reproduce colour and sound better and have better control over their features. Research in cross-modal correspondences is highly multidisciplinary. Therefore, cooperation between colour scientists, musicologists, psychologists, linguistics, UX/UI designers and computer scientists is strongly recommended.

The future work suggested for this thesis would be a deeper analysis of the gathered data to analyse dependencies between the measured confound variables and sound-colour and colour-sound mappings, the data could be used to experiment with machine learning. The proposed implementation would benefit from code refactoring. The documentation should be written to allow for easier reuse.

Recommended further research directions

This work can be extended in the future in the following directions:

- Deeper analysis of hearing loss, tinnitus or high-frequency loss impact on sonification methods experience.
- Measure the cognitive load during the use of sonification methods.
- Measure the cognitive load during the use of SSD.
- Running usability tests of sonification method and SSD.
- Research in the perception of sound and colour combined with linguistics studies to develop a unified colour-to-sound scale to allow communication about colour between a colour deficient person with another colour deficient person or non-colour deficient [71] [1]. This could be connected to the strong correlation between sound and saturation and maybe explain why sometimes people describe the sound as bright or dark.

- Further investigation into the categorisation of notes into groups.
- More comparison studies between web-based research and controlled laboratory study.

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A Appendix

A.1 Consent form

Welcome to the research in cross-modal correspondences of colour and sound

This is an inquiry about participation in a research project where the main purpose is to study corelation between heard sound and colour associations. In this letter we will give you information about the purpose of the project and what your participation will involve.

Purpose of the study

This study tries to find correlations between colour and sound. The results of the study might help researchers to create suitable sonification method of colour which in the future will be applied in sensory substitution device (SSD). SSD can provide information about colour to people who are visually impaired or colour blind.

Who is responsible for the research project?

Person responsible for this project is Sabina Niewiadomska (sabinan@stud.ntnu.no), student of NTNU in Gjøvik.

What does participation involve for you?

In this research, you will be asked to fill small survey, associate a heard sound with displayed colour, associate a displayed colour to a heard sound, give a feedback about research. The experiment will take around 15 to 20 minutes. Your results will be displayed at the end of study.

Participation is voluntary

Participation in the study is voluntary. If you chose to participate, you can withdraw your consent at any time without giving a reason. All information about you will then be made anonymous. There will be no negative consequences for you if you chose not to participate or later decide to withdraw.

How to withdraw?

To withdraw from the study just close the website. To participate in the study please wear your headphones or turn on your speakers. Participation in the study is possible with the use of smartphone and personal computer.

A.2 Survey

1. How much experience do you have with singing or playing musical instruments?
   Answers: 1 (None) 2 3 4 5 (Professional musician), No opinion
2. How much formal training have you had in colour?,
   Answers: 1 (None) 2 3 4 5 (Working professionally with colours), No opinion
3. Do you experience color while you are listening to music?
   Answers: 1 (never) 2 3 4 5 (always), No opinion
4. Do you experience sound while you are seeing a colour?
   Answers: 1 (never) 2 3 4 5 (always), No opinion

A.3 Instructions

A.3.1 Instructions for Part 1

- Please choose a colour which fits best with a heard sound.
- This answer will not be saved.
- To change colour please move range sliders.
- To listen the sound again tap/click button play.
- If you feel ready click next to start the experiment!

A.3.2 Instructions for Part 2

- Please choose a sound which fits best with a displayed colour.
- This answer will not be saved.
- To change sound please move range sliders.
- If you feel ready click next to start the experiment!

A.4 Feedback

1. Thank you for participation in the test!
2. Before you will see your results please give short feedback about the study and fill post study survey.
3. Is the length of study appropriate?
   Answers: 1 (Too short) 2 3 4 5 (Too long), No opinion
4. Could you hear all sounds?
   Answers: 1 (I couldn't hear sounds) 2 3 4 5 (I could hear all sounds), No opinion
5. How bright is the screen of your device?
   Answers: 1 (Very dark) 2 3 4 5 (Very bright), I don't know
6. What device are you using during study participation?
   Answers: Tablet, Smartphone, Personal computer, Other
7. Are you listening sounds of the study on speakers or headphones?
   Answers: My device speakers, Headphones, External speakers, Other
8. Are suffering from any hearing loss?
   No (and I checked it with doctor), No (but I didn't check it with doctor), Yes (and I checked it with doctor), Yes (but I didn't check it with doctor), I might, I don't know
9. Are you experiencing tinnitus (unexpected high-pitched ringing or hissing sound or low pitched sound)?
   Answers: Yes, No, I might, I don't know
10. If you have any comments about the study please share them with me

Thank you for participation in the test!

Before you will see your results please give short feedback about the study and fill post study survey.

Is the length of study appropriate?

- 1 (Too short)
- 2
- 3
- 4
- 5 (Too long)
- No opinion

Could you hear all sounds?

- 1 (I couldn't hear sounds)
- 2
- 3
- 4
- 5 (I could hear all sounds)
- No opinion

How bright is the screen of your device?

- 1 (Very dark)
- 2
- 3
- 4
- 5 (Very bright)
- I don't know

What device are you using during study participation?

- Tablet
- Smartphone
- Personal computer
- Other

Are you listening sounds of the study on speakers or headphones?

- My device speakers
- Headphones
- External speakers
- Other

Are suffering from any hearing loss?

- No (and I checked it with doctor)
- No (but I didn't check it with doctor)
- Yes (and I checked it with doctor)
- Yes (but I didn't check it with doctor)
- I might
- I don't know

Are you experiencing tinnitus (unexpected high-pitched ringing or hissing sound or low pitched sound)?

- Yes
- No
- I might
- I don't know

If you have any comments about the study please share them with me:

Next

Figure 42: Feedback

A.5 Additional colours

Yellow

- hsl(60, 100%, 50%)
- hsl(60, 50%, 50%)
- hsl(60, 100%, 80%)
- hsl(60, 100%, 20%)

Red

- hsl(0, 100%, 50%)
- hsl(0, 50%, 50%)
- hsl(0, 100%, 80%)
- hsl(0, 100%, 20%)

Green

- hsl(120, 100%, 50%)
- hsl(120, 50%, 50%)
- hsl(120, 100%, 80%)
- hsl(120, 100%, 20%)

Blue

- hsl(240, 100%, 50%)
- hsl(240, 50%, 50%)
- hsl(240, 100%, 80%)
- hsl(240, 100%, 20%)

Black

- hsl(0, 0%, 0%)

White

- hsl(0, 100%, 100%)

A.6 Implementation

A.6.1 Research data

"research": [
"low2": ["note":"C2", "note":"D2", "note":"E2", "note":"F2", "note":"G2", "note":"A2", "note":"B2"],
"low3": ["note":"C3", "note":"D3", "note":"E3", "note":"F3", "note":"G3", "note":"A3", "note":"B3"],
"medium": ["note":"C4", "note":"D4", "note":"E4", "note":"F4", "note":"G4", "note":"A4", "note":"B4"],
"high5": ["note":"C5", "note":"D5", "note":"E5", "note":"F5", "note":"G5", "note":"A5", "note":"B5"],
"high6": ["note":"C6", "note":"D6", "note":"E6", "note":"F6", "note":"G6", "note":"A6", "note":"B6"]
]

A.7 Experiment results

User experience of implemented solution

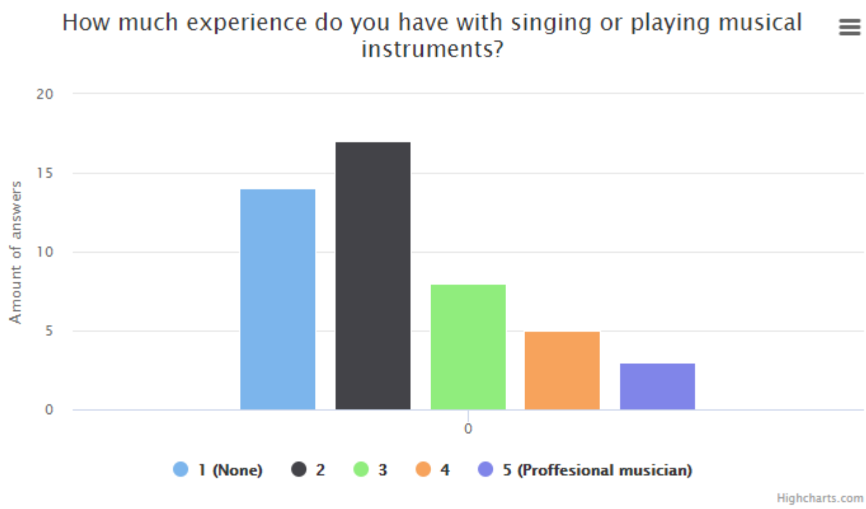

Figure 43: Sound professional experience

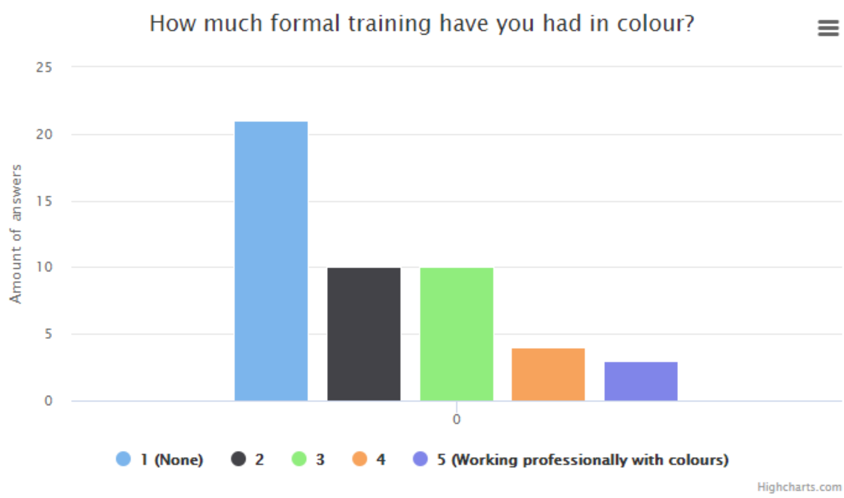

Figure 44: Colour professional experience

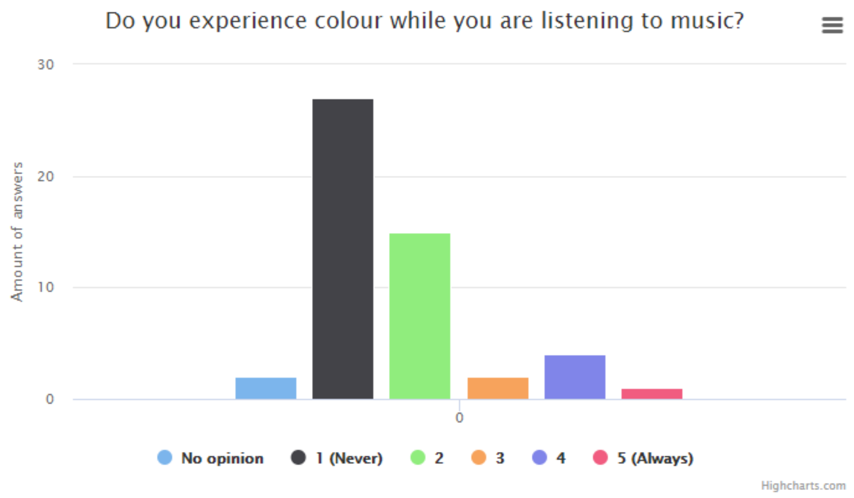

Figure 45: Experiences of colour while listening to a sound

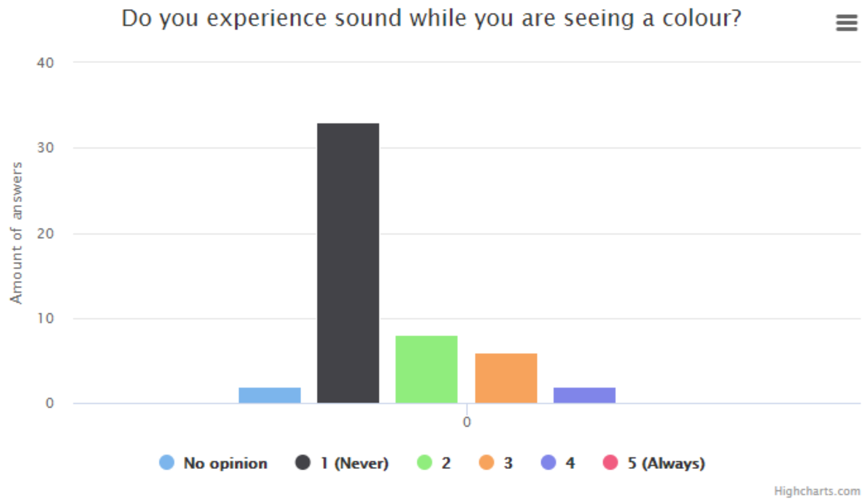

Figure 46: Experiences of sound while seeing a colour

NTNU
Norwegian University of
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