Can VR Help Understand Auditory-Visual Associations and Synaesthesia Through Immersive Battery Tests?

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***Abstract*—This paper gives an overview of my PhD research in the area of auditory-visual associations in Human-Computer Interaction (HCI). My project explores the condition called synaesthesia, and auditory-visual cross-modal associations, in order to gain a better understanding of how our auditory and visual senses combine to inform our perceptive and decision-makings skills. I seek to understand how technology can be used to help strengthen our auditory-visual associations. Previous work suggests that creating effective and immersive environments using Virtual Reality (VR) can help in gaining new insights into auditory-visual perception. Firstly, I will create a VR version of standard auditory-visual and synaesthesia tests, and conduct user studies using both traditional and the VR based tests, with a comparison of the results being investigated to see what impact using a more immersive environment, like VR, has on auditory-visual associations. Secondly, armed with new knowledge concerning auditory-visual associations using VR, I will create a framework that uses auditory-visual associations to help designers create interfaces that are personalised, adaptive and accessible to everyone.**

***Index Terms*—auditory-visual associations, synaesthesia, virtual reality, music**

I. Motivation and Research Questions

Virtual Reality (VR) has become a popular and increasingly-used technology in recent years, with prices and size of headsets decreasing and the technological capabilities increasing, it has become a very useful tool in scientific experimentation (see [1], [2]). My research interests involve gaining a meaningful understanding of music and non-speech sound in general, and their effects on the visual sense, while pushing the boundaries of our creative capabilities. Using VR as a platform for the exploration of auditory-visual cross-modal associations and the condition called synaesthesia (see Section II-A for description), new knowledge can be created that can shape our understanding of the relationship between the senses and how they can be used to make our interactions more effective.

Previously, auditory-visual associations were understood by conducting tests using pen and paper or standard computing devices. Many different types of tests have been used to understand associations between the auditory and visual senses and the condition called synaesthesia [3]–[7]. These tests have been useful in furthering our understanding of associations between the senses. However, with access to new technologies like Virtual Reality, can developing and adapting these auditory-visual and synaesthesia tests using more immersive environments give us a better understanding of how we form associations between our senses? Can synthesizing synaesthetic perception using VR help users gain the creative benefits that have been shown in people with synaesthesia (see [8])?

To breakdown the question above into research questions for my PhD, that will help towards this ultimate goal, I present three questions.

- **Q1:** Can research into an immersive platform, like Virtual Reality, show the potential to be a more effective testing environment for auditory-visual associations/synaesthesia tests?
- **Q2:** Will there be a difference in the results from auditory-visual/synaesthesia tests in VR compared to the tests performed using standard (i.e., non-VR) methods?
- **Q3:** Can a personalised, congruent, auditory-visual profile, similar to synaesthesia, and captured in the aforementioned application, strengthen associations between the two senses and amplify creativity?

In Section II, a background on synaesthesia, auditory-visual associations, the different testing methods and related work in VR will be presented. This will be followed by the methodology in Section III and Section IV will look at my contributions so far and future work, finishing with Section V that outlines how my research contributes to Affective Computing.

II. Background

A. Synaesthesia

Synaesthesia is a rare condition that affects around 2-4% of the population. It can arise as one sense (an inducer) receives stimulation that triggers a reaction in an unstimulated second sense (a concurrent) [9].

Chromaesthesia is a type of synaesthesia between the auditory and visual senses, and affects around 0.2% of the population [10]. Within synaesthesia, the person can have very

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different experiences in a number of ways. Firstly, people with synaesthesia can be categorised as either projectors and associators. Projectors describe their experiences as, seeing colours which are often projected outside the body and into external space. Associators describe experiencing colours in "the minds eye" or "knowing the colour" when a different sensory module is stimulated [9]. The second experiential difference is that there is no single correct association between auditory and visual stimuli, with each synaesthete having an individual association [11]. VR has the potential to deliver an immersive synaesthesia-type experience to the general population, that could be compared to the projector synaesthete's viewpoint.

Another characteristic of synaesthesia that has been found in past research, is that synaesthetes tend to be seven times more creative then non synaesthetes [8]. VR has the ability to simulate synaesthesia experiences and explore areas such as enhanced creativity and adaptive learning for the general population. Creativity research has shown that originality is the main component of creativity but must also involve some other aspect like effectiveness, which might take the form of usefulness, fit or appropriateness [12]. With VR technology still been relatively new to research, applications created in a VR environment have a sense of originality, with the potential to strengthen our associations between your senses providing usefulness in terms of adaptive learning and future interface design interactions. A study by Lee et al., [13], shows how VR can help support creativity as well as cognitive action with the area of fashion design. When comparing a 2D digital tool to a VR design tool, it was shown that the VR design tool had 1.7 times more cognitive design actions and also had a higher percentage of perceptual and conceptual design actions than the 2D digital tool [13].

B. Auditory-Visual Cross-Modal Associations

Similarities between synaesthesia and normal cross-modal associations have been found [5], [14], [15]. Research into auditory-visual associations has found certain associations that are seen in the general population. Higher-pitched sounds have been found to associate with brighter colours, while lower sounds associate with darker colours [9], [14], [16]. Musical key, also can impact how we perceive colours, with the major key associating with brighter colours and the opposite for the minor key [17]. Other associations that have been studied previously are between timbre and saturation, loudness and brightness and pitch and size, to name a few [18].

Emotion can play a vital role in understanding associations between the auditory and visual senses. According to the emotion mediation hypothesis, when a person listens to music they have emotional responses and pick colors with similar emotional content [17]. In [17], [19], they tested the emotion mediation hypothesis on associations between sound and colour and the results showed a high consistency for the hypothesis. Plutchik's wheel of emotions and Hevner's model both use a wheel-like structure to inform associations between emotion and, colour in Plutchik's case, and music in Hevner's case [20], [21]. Understanding how emotion can impact our perception can play an important role in designing new systems, especially in more immersive environments like VR.

C. Auditory-Visual Association Tests

Several different tests have been created to understand synaesthesia and cross-modal associations in the population. The goal of my PhD research is to investigate these different tests and look to replicate and improve them in a VR environment. This section will explore the Implicit Association Test (IAT), Synaesthesia Battery, Test of Genuineness (TOG-R), NeCoSyn method and an Altered State of Consciousness test (OAV) below to give more of a background.

1) Implicit Association Test (IAT): The IAT has been used in previous research to understand cross-modal associations. It is a popular tool to use when studying both implicit and explicit associations between different items [4]. In [4], they replicated several classic cross-modal association tests as well as highlighting two new correspondences with their modified IAT test. They studied the takete-maluma, mil-mal and audio pitch-size of visual object, as well as presenting new cross-modal correspondences between audio pitch-size of visual angle and between waveform-spikiness/roundedness of visual stimuli.

In [5], a test was conducted using the implicit association test (IAT) to explore associations between auditory pitch-visual elevation, auditory pitch-visual size and auditory pseudo words-visual shapes in synaesthetes and non-synaesthetes. It found the idea of a continuum between synaesthesia and cross-modal correspondences is only partly consistent. The IAT method might be a useful test to implement in VR with added visual and spatial audio that can enhance the experience of associations between the senses.

2) Synaesthesia Battery: `The Synesthesia Battery test`[1] is used to determine if a person can be considered a synaesthete or not, with tests for many of the 60+ types of conditions that are known being available on this testing platform [10]. The synaesthesia battery test is one of the most used tests for synaesthesia research to date. It has been validated and has shown to use a valid methodology for assessing synaesthesia [3]. It is usually used as part of an experiment to find true synaesthetes and separate them from control participants. However, it also has the potential to test non-synaesthetes to understand the strength of their associations between the auditory and visual senses, viewing it on a spectrum between high synaesthete-like level to a low non-synaesthete-like level. In [22], it was found that non-synaesthete participants, who took the Synaesthesia Battery test, scored very differently on the spectrum and in the follow up comments section found that participants closer to the synaesthesia end of the spectrum mentioned more detailed colour associations that they experienced.

Other methods have been used along side it, like the IAT [11] or OAV test [23] to first find people with synaesthesia and

[1]https://synesthete.ircn.jp/home

then test and compare to non-synaesthetes. These tests have also created a discussion regarding the relationship between synaesthesia and cross-modal correspondences and the idea of a continuum between them [5], [24]. If we are to judge synaesthesia as part of a continuum with cross-modal associations, the Synaesthesia Battery test can help us understand the strength of people's associations on this continuum.

3) Test of Genuineness (TOG-R): The Test of Genuineness (TOG) has been used and improved on throughout the years as the central tenet for assessing the consistency of synaesthetes reports [6]. Baron-Cohen made great improvements on the TOG method in his works in 1987,1993,1996 but these tests did not include tests for the auditory sense [25]–[27].

The revised Test of Genuineness (TOG-R) was introduced by Asher et al, featuring new material, and a more precise scoring system [6]. It included 48 sounds (instrumental, natural occurring, man-made environmental sounds and vocal exclamations) and used the Cambridge Synaesthesia charts that consisted of 238 numbered colours. This test showed a consistency of 71.3% for synaesthetes and 33% for non-synaesthetes, suggesting that this test can accurately distinguish between the two groups [6].

In [24], some studies support the fact that there was a difference between synaesthesia and cross-modal correspondence and the suggestion of weak synaesthesia was downplayed. The TOG-R seems to have a similar testing method as The Synaesthesia Battery and has potential to crossover into a virtual reality testing scenario easily.

4) NeCoSyn: The NeCoSyn test was developed by Campen and Froger to understand the personal profiles of color synaesthesia. It is based on the Swedish Natural Color system and the TOG for color-word synaesthetes, mentioned in Section II-C3, and it provides individual profiles of color synaesthesia in the dimensions of hue, chroma and blackness [7]. It can test for associations between color-word, color-taste, color-odor, and color-music.

In [7], they refer to cross-sensory correspondence in "normal" people as general synaesthesia, and synaesthesia as we know it as "particular" synaesthesia. They found that "particular" synaesthesia is related to the dimension of hue, while general synaesthesia is related to the dimension of blackness. Also from there results, we can see, for color-music synaesthesia that chroma has a higher consistency than blackness and hue which could be an important aspect in designing synaesthetic associations between the two senses. While this again is an improvement on the TOG test especially for color-music associations and has some similarities to the TOG-R test, it could be an interesting research direction in designing personal color profiles based on synaesthetic associations for "normal" people.

5) Other Tests: The other tests relating to synaesthesia or cross-modal correspondence are mostly based on the tests presented above and are not dissected thoroughly in summaries into the field [11], [24]. The OAV test, while not a test for cross-modal correspondence or synaesthesia, is a questionnaire to assess alterations of consciousness during music listening [23]. In [23], results showed that most synaesthetes, but no controls (non-synaesthetes) reported alterations of consciousness during the test.

It could be an important aspect to study and within a VR space might present more promising results for non-synaesthetes where we could see more out-of-body experiences, alterations of time and alterations in limb ownership, as was presented in [23] for most participants in the synaesthetes group.

D. Related Work in Virtual Reality

Related research work, regarding different assessment tests within a virtual reality environment are sparse. To date, I have found little information on any VR studies on auditory-visual association tests but there are a few other areas that have conducted similar tests with a VR environment.

In [28], an experiment was conducted to compare stress perception in VR and on a regular desktop. This was done using a Stroop word color test, and found that stressful tasks were perceived to be less stressful in the VR environment than on a desktop if no additional stress factors, such as head movement were involved. In a follow up study, the authors created an open-source Stroop room, which is a virtual reality enhanced Stroop test, where they found a 30-40% improvement in some metrics when compared to the traditional Stroop test [29].

In [30], a study was carried out to understand the optimal arousal level for an individual to improve performance. Again, a word-color Stroop test was conducted in VR, with the background presenting different levels of stress in the form of driving through a wartime scenario. They were able to identify the optimal arousal level and found that moderate levels of arousal can lead to improved performance. Parsons and Phillips reviewed different psychological assessments in relation to clinical practices and how VR can be used to improve these assessments. They looked at three virtual environments (virtual classroom, virtual grocery store and a virtual apartment), to understand more about patients, with different ailments, and what they needed to get better [31]. Assessments in VR have the power to add more ecological validity, where more traditional measures of assessment might lack [31].

While these different studies have shown that VR can help improve on certain tests like the Stroop test, there is still a lack of research into the use of VR for synaesthesia or auditory-visual cross-modal correspondence tests. There is a gap in this area where we can build upon the previous work to, firstly, develop a more effective test environment that will lead to clearer and more reliable data and, secondly, help build the understanding of how we should be designing auditory-visual interactions in VR environments that can help in adaptive learning and understand emotions role in associations between senses.

III. Methodology

The methodology for my PhD research, that will help me answer the three questions posed in Section I will be presented

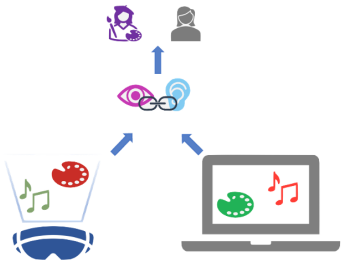

Fig. 1. Process of my research question on comparing VR to standard testing methods in Auditory-Visual Associations

in this section where I will highlight what has been done already and what is left to do. I have reviewed previous research and literature in multiple disciplines that align with my research, these include synaesthesia, auditory-visual cross-modal associations, virtual reality, sonification, digital art, affective computing, and human-computer interaction. An understanding of how single musical notes associate with visual aspects such as colour and also what impact emotion has on the association was investigated in a more standard setting outside of a virtual environment [22].

To help answer research questions, Q1, Q2 and Q3, I will take all my knowledge gained in the different areas mentioned previously and build a VR experience that will give the users a more immersive and emotionally-driven environment where I can test how they form associations between their auditory and visual senses. This will be built in Unity, using an Oculus Quest 2 for debugging and testing. Next, I will conduct an experiment where users will be tested for their auditory-visual associations on standard desktop tests mentioned in Section II-C and then using the VR program. The users' emotional insights on their auditory-visual associations in both tests will also be captured to understand the role of emotion in associations between the senses, which will also help towards testing more personalised profiles. These steps will inform the first two questions from my research proposal, and the results from the data will help shape the design of a more personalised system to test if auditory-visual associations or synaesthesia-like experiences can strengthen the associations between the two senses and impact creativity.

IV. Previous Contributions and Future Work

During the first year of my PhD, I focused on the required modules for my program and researching the different areas of interest for my research area outside of virtual reality. These areas of focus were synaesthesia, auditory-visual cross modal associations, emotion and personality research. I contributed to the publication of three conference papers that were submitted and accepted to two conferences. One paper was published for the Affective Computing and Intelligent Interaction (ACII) conference [32] and two papers were published for the International Conference on Multimodal Interaction (ICMI) [33], [34].

This year I moved my research focus into the VR space and started learning Unity and how to create VR applications. This next year, I will continue my research into auditory and visual senses within VR environments and I will start to create the VR auditory-visual association test and conduct an experiment to compare the VR version of the test with the standard desktop test.

I will follow up this experiment by creating a framework for more personalised mappings on auditory-visual associations in a VR environment to see if this personalised profile can strengthen participants' auditory-visual associations. I am hoping the Doctoral Consortium will connect me with other researchers in my area to create a network of people that can support each other and collaborated in the research field. I am also taking part in work experience as part of my program and the consortium would be a good way to find opportunities either with industry partners or in a research lab to undertake this.

V. Contribution to Affective Computing

My research proposal looks to investigate standard association tests using the auditory and visual senses and adapt these tests using newer technologies, such as VR. By comparing the results of both the standard and VR tests, we can understand if testing in a more immersive environment improves on the scores and helps the participants form stronger associations between the auditory and visual senses. Research into VR has not only shown efficient creation of learning contexts but has shown its use in enhancing affect, with different degrees of influence over the user's emotive states [35]. Riva et.al. conducted a study in which they observed participants' interactions with virtual environments which were based on parks and manipulated to be variously relaxing or to induce anxiety (e.g. sound and music, shadows, lights and textures) [36]. The results showed that the feeling of presence increased in the emotional environment, with the emotional state influencing the level of presence. The VR application I propose, to test associations between the auditory and visual senses, will also provide a contribution to Affective Computing. As mentioned in Section II-B and III, emotion plays a vital role in how we associate between our senses, and participants' emotional state will be captured during both tests. It will provide other researchers with a new tool to be used in research regarding auditory-visual associations or other similar areas. I think VR can be an invaluable tool for research in Affective Computing and we can see interesting research already being done in the field with VR [37]–[40]. Previously, I have contributed two papers to the affective computing field, investigating auditory-visual-emotion associations [22] and also transactive memory systems using a virtual agent [32]. I am excited to move my research forward into the virtual reality sphere, where I believe new knowledge can be built on top of previous research in affective computing and other similar fields.

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