COLOR ASSOCIATION WITH DIFFERENTIAL WAVEFORM DRIVEN FORCE-FEEDBACK VIBRATION PERIODICITIES

A Dissertation by

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I have examined the final copy of this dissertation for form and content, and recommended that it be accepted in partial fulfillment of the requirement for the degree of Doctor of Philosophy in Psychology with a major in Human Factors

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DEDICATION

To Dr. Randall C. Chambers, Professor Emeritus, Wichita State University

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ABSTRACT

This study investigated the relationship between visual stimulus sinusoidal spatial frequency, force-feedback (FF) square, triangle, and sinusoidal wave driven vibrational periodicities, and their association with the visible light spectrum colors ROYGBIV. A customized FF joystick program presented randomly ordered .01, .015, .03, .045, and .09 seconds-per-cycle period FF vibrations while soliciting participant color-choice. Each vibration was randomly presented 10 times across 50 trials. Analyses indicate significant but differing color-association preferences for square, triangle, and sine waveform driven vibrations.

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CHAPTER I

INTRODUCTION

The field of cross-modality sensation and perception research has been around for hundreds of years—even as early as 1704 when Newton pursued association of colors of the light spectrum, via his color-wheel and light decomposition experiments, with the seven tones of the diatonic scale (Newton, 1704). However, cross-modality sensation and perception will perhaps never be as accentuated as it might be during the future development of multimedia internet access, continued software program development, and the evolution of higher levels of virtual reality.

The scope and range of cross-modal sensory perception research varies from that of the phenomenon of synesthesia—a phenomenon where the stimulation of one sensory modality reliably causes a perception in one or more different senses (Cytowic, 1995), to that of the vibration transfer and its effect on pilot performance (Garland, Wise, & Hopkins, 1999). The synesthesia experience is often represented via descriptions of individuals' experiences whereby they suddenly have strange cross-sensory experiences such as a specific taste in their mouth upon seeing a specific color, or seeing specific colors upon hearing certain tones or types of musical stimuli—an assortment of experiences by no means limited to these specific combinations. However, science has had a daunting and questionably productive obsession with synesthesia in its pure form—in fact, why is it that science is continually obsessed with synesthetes who comprise such as small percentage of the population? There is little practical sense in continually studying that which cannot be inferred in any degree to the 'normal' population. Analogously, discovering that pirates with wooden legs walk with a limp is very limited in its ability to tell us about the everyday mobility of the average person. The spirit of this investigation breaks away from the perseveration of synesthesia research and looks at the manner in which the everyday person orders his/her world regarding a novel cross-sensory modality vibrational/visual stimulus association.

It is the aforementioned vibrational cross-modal sensory experience that is the thrust of this paper. New multimedia devices are gradually bringing the issue of cross-sensory modality experiences to the forefront of the consumer experience. The recent integration of haptics and cellular phone design—as well as its integration within force-feedback and video games, simulation training environments, and virtual reality is one example. ‘Vibration’ itself per se, has its own place in such areas as aeronautical research—whereby it has importance regarding such issues as the dynamic vibration environment experienced by the pilot with respect to such factors as maneuver loads, wing loading, gust sensitivity, atmospheric conditions, turbulence, aircraft size, structural bending moments, airframe resonant frequency, and the aircraft’s true airspeed (Garland et al., 1999). Researchers have found critical links between pilot performance under certain vibrational conditions. For example, reaction time to a thrust change command can be almost four-fold during vibration exposure vs. the non-vibratory control period (Garland et al., 1999).

According to the Merriam-Webster Dictionary, ‘vibration’ is defined as: “a periodic motion of the particles of an elastic body or medium in alternately opposite directions from the position of equilibrium when that equilibrium has been disturbed (as when a stretched cord produces musical tones or molecules in the air transmit sounds to the ear).” ‘Haptic’, as per Merriam-Webster, can be defined as follows: from Greek ‘haptesthai’ to touch; relating to or based on the sense of touch; characterized by a predilection for the sense of touch.

‘Proprioceptive’ is indicated as being “of, relating to, or being stimuli arising within the organism”—which appears to be reference to an internal feedback system that arises within the individual. The term ‘kinesthesia’ is defined as: “a sense mediated by end organs located in muscles, tendons, and joints and stimulated by bodily movements and tensions, or a sensory experience derived from this sense.” The kinesthetic system is at times referred to as a system providing feedback regarding one’s body positioning in three-dimensional space.

CHAPTER II

LITERATURE REVIEW

Cross-sensory Modalities: Touch, Vision, and Audition

There exist a number of research endeavors aimed at understanding the specific cross-modal combination of touch and vision within information processing—nearly all of which directly relate to concrete elements of the present study. The exploration of stimuli using the hands and the sense of touch, as well as the positioning of the limbs in three-dimensional space is of great relevance for a cross-modality study of vibrational period response and its association to specific visual stimuli.

In a study by Lederman and Taylor (1969) that used object tactile exploration, they allowed participants to freely use any touching method they desired with the constraint that they not use any type of 'measuring device' such as fingertip-spread. Their hypothesis was that the allowance of such exploration would garner object identification results similar to that of vision. Their study in fact found such similarities, but also found differences between these modalities—namely, the interpolation of object angles, and constant errors of touch that are nearly twice as large as those found in vision. Similarly, in a study by Lederman and Abbott (1981) it was found that perception of surface texture is weighted about evenly when vision and touch are presented with discrepant information—a result indicating that judged perception of the surface texture was derived from the mean of the discrepant visual and touch information as presented. In addition, their findings indicated that use of touch, vision, or touch and vision, led to performance on a texture identification task yielding comparable matching accuracy and precision—thus signifying that individual sensory presentations and cross-modal sensory presentations do not differ in their ability to facilitate identification of surface texture.

Texture perception was also the main focus in a study by Wall and Harwin (2001) who investigated roughness perception of simulated surfaces through the haptic and visual senses. Most importantly, and relevant to the present study, this investigation looked at differing spatial frequencies and waveform amplitudes for stimuli, such as those that are found in higher amplitude high spatial frequency square wave gratings (Figure 1) to lower spatial frequency lower amplitude sinusoidal wave (Figure 2) and triangle wave (Figure 3) grating representations.

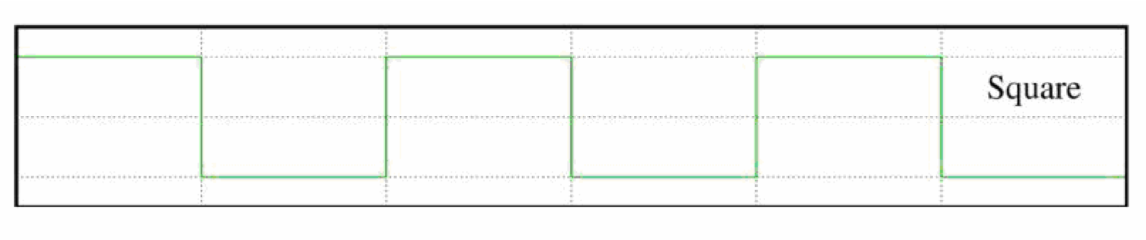


Figure 1. Square waveform of 2.5 cycles (www.Wikipedia.org)

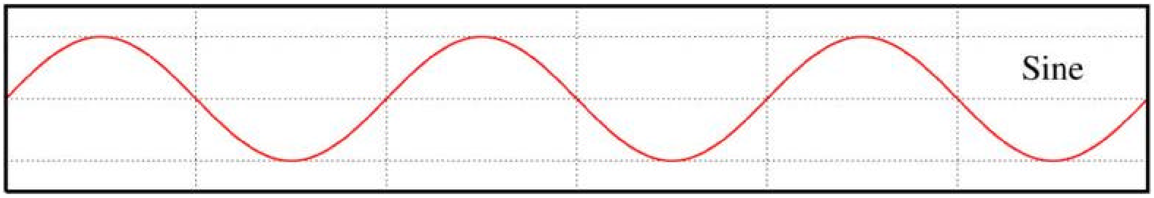


Figure 2. Sinusoidal waveform of 3 cycles (www.Wikipedia.org)

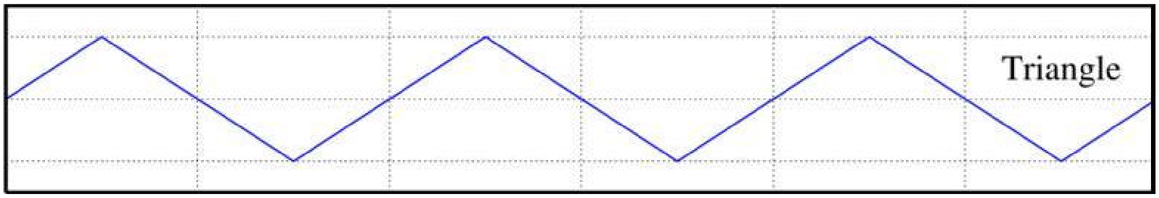


Figure 3. Triangle waveform of 3 cycles (www.Wikipedia.org)

A specialized 3-degree of freedom (3-DOF) haptic interface program called PHANToM was used to make graphical representations of “virtual gratings” of the differing visuo-spatial frequencies. Participants were presented different virtual gratings on the “wall” of the program’s interface workspace in the visual condition. For the haptic condition, participants were able to feel the sequential rise and fall of sinusoidal structured surfaces that consists of peaks and valleys. Spatial periods of the test surfaces for both visual and haptic conditions varied from .5mm and 3.5mm in increments of .125mm generating a test set of 25 different surface representations. Participants were instructed to assign a ‘standard’ (control/comparison) surface 100 ‘roughness’ units (a ‘magnitude’ estimation), and then for trials were asked to provide a number for each of the test surfaces that represented the perceived roughness relative to the standard. Haptics condition results indicated that 25% of the participants did not indicate a significant relationship between varying spatial frequency periods and magnitude of roughness judgment. However, within the visual condition all subjects showed a significant relationship between spatial period and roughness magnitude. These results appear to point out that the nature by which roughness perception that occurs under visual inspection, as opposed to haptic exploration, seemingly differs.

An unusual haptics-audition cross-modal sensory mapping experiment was undertaken by van den Doel (2003), consisting of an interactive software program called SoundView, which allows the user to explore a color image through touch and hearing. The SoundView program consists of a program interface that conveys a fine-grained color dependent roughness texture. The user can explore the interface by moving a pointer over the image, which causes a sort of virtual gramophone response on the part of the program as it ‘reads’ the cursor movement similar to the manner in which a gramophone needle vibrates in response to the grooves of an analog LP recorded disc. The sound produced by the program is dependent upon the movement of the ‘needle/cursor’ as well as the color of the area that is being explored. Although an extremely interesting program in its own right, it apparently relies upon a purely subjective algorithm in determining exactly what specific types/pitches of sounds are matched with specific hues of color. Nevertheless, SoundView represents a breakthrough in direct multi-modal multimedia experiencing by providing one of the first program platforms that attempts to legitimize the confluence of a relationship that could have a very large impact on the future of advertising, virtual reality, gaming, and other yet to be determined multi-sensory experiences.

In a study by Berger and Hatwell (1995), the focus was on the development of dimensional vs. global processing in haptics—specifically, perceptual and decisional determining factors contributing to classification skills for adults and 5 to 9 year-old children. Stimuli were varied along texture density and hardness dimensions in order to determine if the analytical and sequential aspects of haptic exploration would prevent participants from accessing the whole object. Participants reached through a curtain to haptically explore objects across condition manipulations that consisted of that such as the presence of a to-be-judged ‘hardness’ surface and to-be-judged ‘texture’ surfaces for stimuli, or the combining or hardness with texture within a presented surface. Their findings did not support their hypothesized assumption that classification would be based more often on identification of the ‘relations of parts’ and less on ‘similarity’ between parts. However, their findings do provide the indication that participants tend to process texture density and hardness dimensions more analytically and less globally with age—that for adults, exploratory procedures are more specialized and less general than are those used by children.

The combining of sensory information across modalities can also result in degradation of primary cue information resulting in the loss of these primary cues to some degree. Thus the combining of such information would be generating a unique type of ‘emergent’ informational cue rather than allowing the independent contribution of informational cue from each modality to remain independent in its contribution. In just such an investigation, Hillis, Ernst, Banks, and Landy (2002) found that there was an ‘opportunity cost’ associated with the combining of information across cues in order to improve the estimation of the properties of objects. Their findings indicated that single-cue information was lost when cues from within the same sensory modality (e.g. disparity and texture gradients in vision) were combined, but no information loss occurs when different modalities (e.g., vision and haptics) were combined. Specifically, the indication is that there is occurrence of a depth-cue fusion—shape information from disparity and texture cues combines to create a single fused percept—a percept that, although capable of facilitating discriminations that could be made from single-cue estimates, does not do so. Additionally, they cite evidence of a single, fused percept for shape information from combining haptics and vision—an intermodal percept that does retain single-cue estimate information.

Eimer, van Velzen, and Driver (2002) measured the event related potentials (ERP) for tactile, visual, and audition sensory modalities in stimulus presentation trials designed to ascertain levels of possible cross-modal interaction. One important finding of this study was indication that visual and auditory ERPs were affected by spatial attention when touch-response was relevant to task performance, revealing cross-modal interactions—specifically that when audition was relevant, visual ERP's but not tactile ERP's were affected by spatial attention—with the ultimate indication from these results being that tactile sense can be detached from cross modal processing attention when it is task-irrelevant. These results from Eimer et al are related to the current study due to the design framework of the current experiment consisting of constant white noise exposure for participants during presentation of vibrational periodicities/frequencies, and subsequent color-matching choices rendered to these vibrational stimuli by participants across trials. Simply put, the effect that the auditory-experience neutralizing white noise has on the current experiments cross-modal task response of color selection in response to vibrational force-feedback periodicities, must garner consideration up front as a potential confound ultimately rendering results as weakened or tainted.

The perceptual influence of visual and auditory stimuli on a virtual object presented via a haptic interface device was the directive of Miner, Gillespie, and Caudell (2005). Their investigation focused on a participant manipulated device called "The Moose" that consists of a 'puck' that generates reflecting forces for differing surface representations such as that of a 'hard' or a 'soft' surface. As participants manipulate the puck, the dual motors of the Moose can produce continuous forces in excess of 25 Newton's. The experimental paradigm was to introduce the presence of visual and/or auditory stimuli during haptic perception, so as to determine if such information could influence participants to perceive larger or smaller forces than they were actually experiencing via 'The Moose.' Ultimately, their results indicate that participants could be influenced by visual stimuli alone and visual plus auditory stimuli together—but were not influenced by auditory stimuli alone.

Withholding/Manipulating Visual Feedback: Reliance on Tactile Feedback

Jordan (1972) investigated the relationship of proprioception as related to visual processing, proprioceptive response times and motor skill acquisition during a condition that withheld visual feedback. It was hypothesized that depriving participants of visual feedback during early stages of motor skill learning would allow the subject to focus their attention on proprioceptive feedback thereby measured by faster responses. The results of this study suggest withholding of visual input during early stages of motor skill learning force the subject to rely on proprioceptive feedback—the indication being that those deprived of such visual learning pre-task experiences, are seemingly using a different system than that exhibited by pre-task visual training motor skill participants. This is an important finding in relation to the present study in that it provides some evidence of proprioceptive awareness and visual processing demands/skills and vice versa.

Similarly, Heller (1992) built upon that as aforementioned by Jordan (1972) by looking at the manipulation of visual feedback rather than blatantly withholding visual feedback. Heller brought touch and vision in conflict with one another by using a mirror placed perpendicular to a letter display that participants were to proprioceptively interact with. The mirror position caused a discrepancy in guidance/direction and in perceived form of the target participants were to touch. Participants touched embossed tangible raised letters while looking at them in the mirror and were asked to identify them. The mirror produced a vertical inversion of the letters, and a visual inversion of the direction of finger movement. So, for example, participants touched the letter ‘p’, but actually saw themselves touching the letter ‘b’ via the mirror. Results indicate that, consistent with an attentional explanation of intersensory dominance, touch dominated vision in form perception when subjects were able to see their exploratory hand movements. Additionally, Heller mentioned that one could expect the difficulty of coordination in such an experiment to be attributable most likely to a vision bias, being that vision has greater processing speed. In addition, the results of this experiment point out that haptic dominance as seen in this type of design could possibly be influenced by using large embossed familiar letter shapes in conjunction with an elevated role of proprioception feedback/influence. Thus, the role of vision cannot seemingly be exclusively credited independent of any contribution by proprioceptive information—and perhaps the idea of an ‘emergent property’ via the combination of the two would be the best explanation of many such experimental results as this. The Heller (1992) study ties in with the present investigation in that one must give consideration to the contribution of ones monitoring of ones body movement in response to a vibrational or haptic stimulus experience. The present study was devoid of such monitoring on the part of participants and excluded all participants from having visual contact with their hand while experiencing the vibrational force-feedback from the joystick. It would be just to acknowledge at this point that the outcome of the present investigation may well differ when visual feedback to a vibrational source is accessible visually, as opposed to being denied completely—that a different experimental configuration could have revealed different results altogether.

In an experiment similar to that of Heller’s, Loomis, Klatzky, and Lederman, (1991) investigated the recognition of pictures from a limited field of view via the tactual and visual recognition domain. Participants attempted recognition of simple line drawings of common objects using either vision or touch. The touch group explored raised line drawings using the distal pad of their index finger or the distal pads of both their index and middle fingers. Those in the visual condition used a computer display to simulate tactile exploration whereby movement of an on-screen digitizing pen moved an on-screen image behind a stationary on-screen aperture, through which the drawing could be viewed. The aperture was varied in width to simulate the use of one or two fingers (e.g., a single aperture width was correlated with the use of one finger in the tactile condition, and the two aperture width was correlated with the use of two fingers in the tactile condition). Results showed that performance for recognition in the one-finger touch condition was essentially the same as compared to the simulated (single-aperture) one-finger visual condition. The visual recognition performance condition however, showed considerable improvement for the two-aperture (two-finger visual simulation) condition—but tactual performance did not show this greater improvement when two fingers were actually used in the actual tactile exploration condition. As mentioned by the authors, and relevant to the current experiment, channel capacity and its determination by temporal and spatial bandwidth can have a direct hand in determination/recognition with respect to comparison of performance in tactile vs. visual tasks. Klatzky, Lederman, and Matula (1993) also investigated the haptic exploration of objects in the presence/absence of vision. Participants compared pairs of objects on certain properties and were either allowed to use vision only or vision in conjunction with touch. Findings indicated support for a model whereby preliminary visual processing can rapidly initiate a process of haptic object exploration when material judgments are visually or semantically difficult.

In a study by Barrett and Krueger (1994) that looked exclusively at proprioceptive feedback, the directive was the manipulation of the presence/absence of familiar kinesthetic and tactile feedback from a keyboard during a touch-typing task on a conventional vs. a prototype piezo-electric flat-profile keyboard (lacking any mechanical key ‘rebound’ response). Participants’ objective performance (e.g., throughput, accuracy, speed, etc) as well as their subjective rating of the differing devices, was measured. Results indicated that the touch typists were unable to adapt to the aberrant feedback responses rendered by the piezo-electric flat keyboard. Albeit this was not a vibrational study and was an ‘active’ touch task regarding sensation via proprioception, these results clearly magnify the importance of accurate feedback as a contributory element in consistency of performance and accurate responses. Should anomalous, inconsistent, and inaccurate vibrational periodicities be the norm for force-feedback within the present study, one would not expect to see any systematic relationships evolve from the data.

Priming/Expectation Effects and Visual/Haptics Response

Another area of interest is the anticipation or ‘expectation’ that participants may develop or already possess going into a research endeavor—and the degree to which this a priori knowledge or experience may influence outcomes or responses. Easton, Srinivas, and Greene (1997) looked at this very issue via implicit vs. explicit memory ‘priming’ regarding same vs. differing modality tasks, and if priming between vision and haptics processing is in some way mediated by presenting modality specific representations of words. Their hypothesis was that larger priming effects should be observed in conditions when words are presented in the same modality between study and test relative to when they are presented in a contrasting modality between study and test. Results indicated that cross-modal transfer was comparable to within-modal transfer, and thus provides evidence that priming and cued-recall modality effects obtained for verbal materials presentation were the result of simultaneous versus sequential processing. Subsequent to these aforementioned findings Easton, Greene, and Srinivas (1997), then looked at the 'non-verbal' domain regarding the assessment of implicit vs. explicit memory, by using both 2-dimensional patterns and 3-dimensional objects within combinations of cross-modal presentations and priming conditions. Their question for this study was: if comparable information was presented to the differing modalities—such as a 2-D or 3-D structure—would visual and haptic representations be sufficiently abstract so as to permit exchange across the modalities or are the representations largely specific to modality? In this study the results of the implicit testing indicates presence of a strong cross-modal priming for both 2-D patterns and 3-D objects, a suggestion that vision and haptics shared abstract representations of object shape and structure. The results of the explicit testing for 3-D objects revealed specificity for modality, an indication that the recognition system tracks the modality via which an object is experienced. Additionally, Lederman, Klatzky, Chataway, and Summers (1990) provide a priori support for these findings via results indicating that the tactile recognition of real common objects (3D tactile exploration) can approach 100% in contrast to significantly decreased object recognition rates (33%) for two-dimensional objects for blindfolded sighted observers. Perhaps the most interesting finding of this study is the indication that visual recognition is was not only identical to haptic recognition—but was equally poor. In addition, the findings of this study argue against the hypothesis that inexperience with tangible graphics displays underlies poor two-dimensional haptic recognition—a result that aids the current study, given the graphical nature of the response stimulus, by providing evidence that those with less computer graphics experience are perhaps more or less 'equal' to experienced graphics/computer users than one might surmise.

In a rather novel study by Young, Tan, and Gray (2003) it was found that by priming an individual with haptic feedback in the form of 'taps' on the back in one of four specified quadrants (e.g. upper right and left; lower right and left), detection-reaction times for a visually presented stimulus in one of four on-screen quadrants would significantly decrease. This was found to be particularly so if the ‘tap’ was relevant to the quadrant that the visual stimulus would appear in. Two groups were utilized; an 80% (high) validity group, where 80% of the ‘taps’ on a quadrant of a participants’ back were in fact the correct location prime for the same on-screen quadrant that the stimulus would appear in; and a 20% (low) validity group. Results indicated that some participants clearly benefited from the cues as opposed to others who were able to learn to ignore the (mostly invalid) haptic cues. Ultimately, as per the authors, this evidence indicates the reorientation of visual and spatial attention is rather natural and intuitive when there is high validity for any available haptic cues.

Jones, Andre, Kubasko, Bokinsky, Tretter, Negishi, Traylor, & Superfine (2004) investigated the potential of touching and manipulating objects so as to lead to a deeper and more comprehensive type of object knowledge that could be obtained from vision or audition alone. The focus of their experiment was the use of a device called the ‘nanoManipulator’ and its ability to allow students to reach out and touch live viruses inside an atomic force microscope. One-half of the students received complete haptic (tactile and kinesthetic) feedback via a haptic joystick, and the remaining half of the students were able to manipulate the viruses but the haptic feedback on the device was absent. The results showed that there were significant gains from pre- to post-instruction fro the two groups regarding relevant knowledge and attitudes. Specifically, changes that were significant included the students’ understanding of scale whereby after instruction they were more likely to identify examples of nano-sized objects and have the capability to describe the degree to which a human would have to shrink to in order to actually reach the size of a virus.

Vibration

Albeit similar to haptics, vibration by earlier mentioned definition indicates emphasis on the properties of the stimulus, and the manner in which sensory mechanisms respond to these characteristics of the stimuli. For example, in the presentation of subtly vibrating icons on a computer screen—a scenario where one is devoid of the ability to sense them haptically—it would be the responsibility of the visual system to process such vibrational information. Thus, the study of ‘vibration’ extends itself into the realm of hearing (vibration via air pressure change) and vision that to a certain extent, excludes haptic sensory processing (however, one can haptically sense sound waves if the sound is appropriately focused and loud enough).

Joel (1935) investigated the tactile perception of vibrations emphasizing that vibrations are merely perceived as vibrational movement of a body in motion. Joel raised an important foundational question regarding a research endeavor of presenting varying haptic/tactile vibrational stimuli and human-rendered judgment of them: “In the physical stimulus there are differences both of frequency and of energy—which of these is the basis of discrimination?” (Joel, 1935, p.269) Albeit, it is not the intent of this research endeavor to ‘tease out’ and isolate these two potential confounds, it is important to note that any results of this research must be undoubtedly related back to Joel’s poignant question.

The results of Joel’s early research indicated that participants discriminated, with respect to quality, only vibrations of differing frequencies that contained energy conditions which also allowed discrimination in terms of intensity. The points of emphasis made here with respect to Joel’s findings, is of critical importance to this study. Ultimately, any cross-modal stimuli pairings between that of color and vibration, must control for vibrational intensity, vibrational frequency, or less preferably—their interaction.

Vibrational periodicities/frequencies have a very direct relationship with vision, such as that which occurs during the direct vibration of an icon that creates an animation type of effect—an attention catching movement. Vibration and movement therefore are inherent to visual stimuli when this vibration remains visual domain specific. Huang, Harada, and Shimizu (2004) investigated the sensing of visual vibrations via animated images/icons and identified the important features of visual-vibration icons as being comprised of the attributes of frequency, edge distinction, amplitude, vibration direction, and appearance. Their findings also recommend a vertical vibration direction so as to increase visual vibration effect, as well as recommendation of circular and square icon shapes over triangular shapes. It is important to point out the stimulus and terminology similarities of the Huang et al. investigation with that of the present study: both contain frequency/periodicity of stimulus oscillation, amplitude of stimulus and vibration direction, as well as the fact that the first experiment of the present study used a pulse waveform to drive vibrational periodicities and the second experiment used a triangle waveform (see Figures 1 and 3). This type of 'shared terminology' and shared stimulus characteristics clearly shows a definitive commonality between vibrational force-feedback stimulus and visual stimulus.

Also of direct importance to the study at hand is the issue that of the relationship of age and vibration sensitivity. Being that the current study has a diverse range of participants the consideration must be raised about potential differences between participants regarding age. It has been known for quite some time that that the cutaneous glomus body functions as a receptor of cutaneous pressure, and that vibratory sensitivity decreases with respect to aging (von Haller-Gilmer, 1942). In addition, albeit beyond the scope of control for the current investigation, von Hiller-Gilmer indicates that peripheral circulation and skin temperature are also related to some degree, to subtle influence over sensing of vibrational frequencies. It is hypothesized that at extremes, this would be a viable concern for the current investigation—e.g. an extreme such as the submersion of a persons hand for five minutes in a bucket of ice water prior to the experiment—a condition that would obviously affect the normal sensation of vibration via cutaneous mechanoreceptors.

In one of the most closely related studies to the current investigation, Brisben, Hsiao, and Johnson (1999) investigated the passive detection of vibrations as transmitted through an object when grasped in the hand, was the investigative focus. The experiment consisted of the passive vibration reception via a 32mm cylinder that was embedded with a motor causing vibration parallel to the axis of the cylinder. The cylinder containing the motor was mounted to a vibration isolation table surface, suspended via monofilament line inside a frame comprised of two nearly circular wheel-rims, one at each end of the cylinder—a suspension system designed to remove the damping effect that the wiring bundle running into the cylinder might have on the vibration at the cylinder grasping point, and to allow free axial movement. The experimental method consisted of the following: 1) Participants would touch the cylinder with the palm of the hand for the vibration trials; 2) simultaneously listen to 100Hz to 15kHz composite white noise so as to mask motor noise/external sounds; 3) have their skin temperatures monitored; 4) participants' thumb was suspended in a type of sling so as to facilitate a 'grasping' of the cylinder only with the four fingers against the palm; 5) stimuli recording via motion monitoring using a triaxial accelerometer for measuring the sinusoidal waveform vibrations with a resolution of 5,000 samples per second.

Trials were begun by hitting a computer key after which an LED would light up for 1.5s along with 100ms 100Hz tone to signal the beginning of an 'interval'. One trial consisted of a three-interval sequence—with each interval potentially containing the vibratory stimulus. For the dependent measure, participants were to identify the interval in which the stimulus occurred by hitting the 1, 2, or 3 key on the keyboard. Experiment 1 contained two intervals while experiments two through five consisted of three interval trials. In experiment one participant's actively gripped the cylinder so as to determine the human capacity to detect transmitted vibration. The results indicated detection thresholds that were less than any previously documented, save for those occurring within a highly similar vibration detection paradigm presented by Bekesy (1939). Experiments 2 through 5 looked at factors contributing to threshold sensitivity for vibrational sensation. For experiment two participants felt active vibration transfer while grasping, and then passive vibrations applied to eight different areas of the open hand—three on the middle finger distally; three on the middle and ring fingers combined; and two on the palm. Experiment three looked at vibration sensing under differing passive contact forces from the device as placed against the skin, and the contact force was varied in five steps from .05 to 1.0 Newton's of force. In experiment four the vibration sensing paradigm was passive and the directive was the comparison of detection thresholds obtained in experiment two with thresholds obtained using a punctate probe at these same experiment two stimulus sites. Experiment five was a balanced 2 x 2 factorial design that was designed to determine the effects of contact area and vibratory (axis) direction. The results of experiments two through five indicate that contact force had no effect over ranges that were tested; a small effect was found with vibration direction—vibration parallel to the skin surface yielded thresholds at 40 and 300Hz that were 1.3 and 3.3dB lower than vibration perpendicular to the skin surface; contact area, probe type; and stimulus location garnered the major effects. In addition to the study itself, Brisben, Hsiao, and Johnson (1999) also emphasize the historical accounts of vibrational studies and the fact that a wide scope of these studies exists due to the large number of variables that can and do affect the perception of vibration—vibration frequency, duration, direction, contact geometry, contact area, contact force, state of adaptation, context (e.g., presence of 'masking'), mode (active vs. passive), skin site, skin temperature, age, and pathology—several of which are aforementioned limitations by von Haller-Gilmer (1942). The current study is conducted without consideration for some of these variables as it is deemed that rigorous controls would yield far less generalizability, and would hinder the reliable inference of any significant results. The intent of the current study is to discover what the normal everyday conditions of a reasonably familiar vibrating force-feedback device yield when experienced by the more or less normal everyday person.

In an active vs. passive touch comparison, Loomis and Lederman (1984) question what utility there might be regarding ability to distinguish between active and passive touch. The thrust of their paper is to organize the literature regarding active vs. passive touch (though devoid of any 'vibration' studies) with respect to actively feeling stimuli/textures in two dimensional and three dimensional modes. This paper does make consideration for hand movement (active experiencing) as well as passive non-movement of the hand and reception of stimuli cutaneously such as having a two-dimensional Braille stimulus passed over the designated touch reception area. They also developed the comparison definitions of 'kinesthetic' vs. 'haptic' a bit further in that kinesthetic perception is that whereby perception is mediated by variations in kinesthetic information, and haptic perception is perception mediated by both cutaneous and kinesthetic information. The current experiment presents the vibrations to the hand while participants grip the joystick; thereby the hand is always in contact with the same familiar surface during passively applied movement of the hand in three-dimensional space, at varying vibrational cycle periodicities. Therefore the present study, as per the above defined parameters by Loomis and Lederman (1984), is an experimental paradigm where mechanoreceptors in the skin are sensitized to the movement of the joystick with the simultaneous contribution of received kinesthetic information transfer from the hand/arm itself to the relevant brain areas for processing. The ultimate question derived for this would be that of dominance—which system, touch/mechanoreceptors and haptic feedback, or kinesthetic movement of the hand through three-dimensional space via the application of FF, is likely to be the prime contributor?

In a related study that adds credence to the question previously raised, Robles de la Torre (2002) found that the lateral forces arising when passively touching different shaped objects can in fact be equal—calling this 'lateral ambiguity'. His study looked at participant exploration and assignment of 'geometryless' lateral-force (LF) based Gaussian virtual surfaces into categories of shape ('holes' and 'bumps'). The stimuli were 'geometryless' in that they reproduced the LF's present when a physical shape is explored—but doing so without vertical movement allowance of a participant's limb as exploration of a normal geometrical shape would. The device used was called a 'manipulandum' and consisted of an attached haptic interface whereby the manipulandum rolled on top of a flat physical surface. Participants used their index finger to roll the manipulandum horizontally and sideways. Simultaneously, the haptic interface would render virtual surfaces.

Results indicated that participant's classification performance declined within passive conditions and achieved high performance levels for the active conditions of exploration. Robles de la Torre's indication is that this lateral force ambiguity as investigated can be used to explore the questions of whether active and passive touch percepts are equivalent, and if they originate in the same brain mechanisms. In addition, Robles de la Torre goes on to indicate that "force is inherently ambiguous when presented passively" (p.5), a statement that will be seen as clearly dispelled and refuted by the current study—so much so, that the crux of this ideology and its underpinnings may require serious re-evaluation.

Limitations and Shortcomings of Force-Feedback/Vibration Paradigms

One limitation of a force-feedback experimental paradigm can be potential interference with accurate transmission of the force-feedback periodicity frequencies rendering a non-realistic experience for the user. In a study addressing this undesirable and ongoing necessity of an umbilical attachment between the haptics user and the computer within a human-computer interaction model, Ye, Corso, Hager, and Okamura (2003) looked at the possibility of eliminating this umbilical attachment due to its hindering of perception of the virtual reality environment. Their solution to the umbilical attachment hindrance problem was the development of the VisHap system. The VisHap system combines a visual tracking system with force-feedback so as to provide a seamless integration across the haptic virtual reality experience. This translates to the current study due to the testing scenario whereby the force-feedback joystick is mounted on a plastic crate positioned in front of the participants. The nature of this type of mounting clearly absorbs some portion of the vibrational energy from the joystick, and could cause this body to absorb critical vibrational periodicity/frequency information that may or may not alter the true picture of the response data.

Another consideration in studies of the relationship between tactile-haptic-vibrational stimuli and visual responses is that of the design of such multi-modal input systems. Keates, Clarkson, and Robinson (2001) endorse these very considerations—the cognitive processing power of the individual and the potential burdening demands of multi-modal input systems—

concluding that cognitive demands on the user may have an adverse effect on the quality of the interaction and on the subsequent quality of participant responses. These findings declare an important caveat for this investigation in that one must be aware that any results of a cross-sensory modality study such as this may seemingly be comprised of random responding, when in fact the stimulus combinations presented may simply be too complex, resulting in a response interaction exceeding the bandwidth processing power of the individual. In short, with too much bandwidth being demanded by a multi-sensory modality task, participant responses may be merely a fraction of their true capability due to the lack of processing bandwidth to handle parallel cross-modal processing of both stimuli simultaneously. Thus, one should not be too quick to abandon a seemingly unfruitful methodology when in fact ‘watering down’ the stimulus combinations and simplifying the demands on the participants may in fact reveal the borderlines/limitations of some task-specific cross-modality sensory processing bandwidth—perhaps a wise decision as opposed to blatant abandonment of an angle of pursuit due to seemingly empty results.

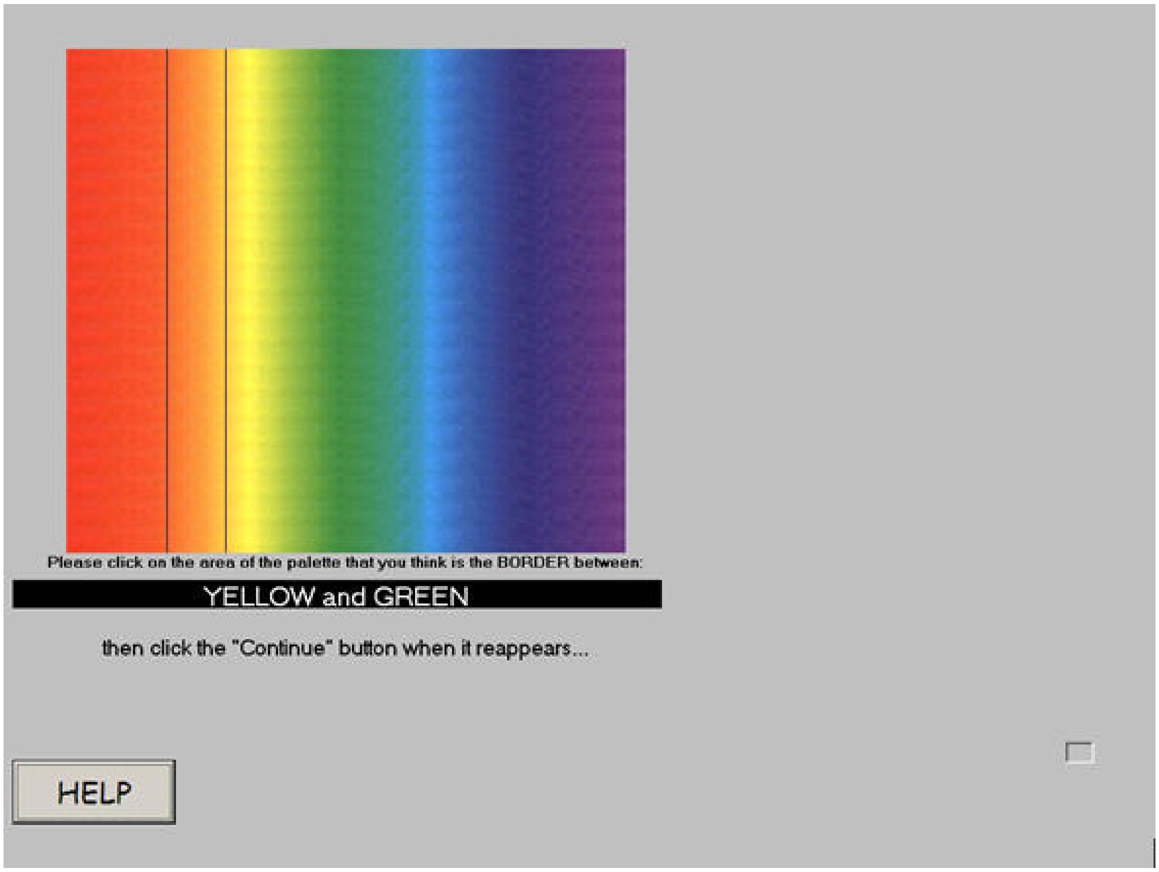
Hypotheses

It was hypothesized that specific FF vibrational periodicities would be associated with specific color choices on the part of participants. In addition, it was also hypothesized that these color-associations would vary with respect to three basic waveforms utilized to drive the FF vibrational periodicities—triangle wave, square wave, and sinusoidal wave.

CHAPTER III

EXPERIMENT 1

The first experiment consisted of a triangle wave driven (Figure 3) force-feedback joystick vibration. Simultaneously, participants were exposed to an interface containing a sinusoidal (Figure 4) color-grating visual stimulus. The primary manipulation within Experiment 1 was the presentation of the force-feedback joystick vibrations at five differing vibrational frequencies.



Please click on the area of the palette that you think is the BORDER between:

YELLOW and GREEN

then click the "Continue" button when it reappears...

Figure 4. Screenshot of interface for Experiments 1-3 during color-defining task on color-picker image

Method

Participants

Fifty graduate and undergraduate students (Experiment 1 = 43 female, 7 male from Wichita State University received partial course credit for their participation.

Materials

The study was completely self-contained using a program written with Microsoft Visual Basic 6.0. The program presented the entire experimental sequence that consisted of 1) demographic information collection, 2) instructions to participants, 3) Color-defining phase, 4) experimental stimulus trials, 5) completion screen, and 6) debriefing information.

Equipment and Apparatus

Computers running the custom software program were Dell Precision Workstation 360 with Windows XP-Pro software, 3 GHz Pentium-4 processor, and 1GB DDR RAM capacity. Monitors were Dell E172FP 17-inch LCD flat-panel with Nvidia Quadro FX 500/600 PCI 128 MB graphics card. The resolution for presentation of the software program was the default setting of 1152 x 864, 75 Hz refresh rate, 32-bit color quality, 96 x 96 DPI. A standard scrolling optical mouse and QWERTY keyboard were used for entry of demographics information and for entering responses to stimulus trials. White noise to mask external environmental sounds and the sound of joystick vibrations was reproduced for participants through Aiwa HP-X222 model stereo headphones. There was also an available volume control available in the event participants found sound levels too discomforting.

The force-feedback joystick was a Logitech Wingman Force 3D, model J-UC10 with a USB direct connection to the computer. The joystick sat on top of a standard black plastic milk crate that measured 16.5 in wide x 10.5 in high x 13.5 deep, and was anchored to the crate using plastic zip-ties. The crate was placed on its end so as to have the joystick sitting on the crate 16.5 inches from floor level. Participants placed one leg on each side of the crate and then would slide forward as close to the table as possible, assuming a position where they had their left hand under the table on the joystick and their right hand on the mouse—all in an effort to eliminate participant visual contact with their hand.

Auditory Stimulus

In order to neutralize participant hearing during experimental trials, participants listened to an mp3 file containing 30 minutes of continuous white noise. This was necessary due to the earlier mentioned fact that participants would be able to actually hear the internal joystick motors 'buzz' during any specific vibration—noise that was not only audible, but was proportional in frequency to the speed with which the motors vibrated. The white noise file was created using GoldWave audio editing program, and the actual frequency contents of the file can be seen in Table 1. Although the file was 30 minutes in length, participants were finished with the experiment in less than 15 minutes.

TABLE 1

WHITE NOISE AUDITORY STIMULUS SPECIFICATIONS

	Left	**Right**
Min Sample Value:	-32768.00	-32768.00
Max Sample Value:	32767.00	32767.00
Peak Amplitude:	0 dB	0 dB
Frequency range:	0Hz – 22kHz	0Hz – 22kHz
Minimum RMS Power:	-9.75 dB	-9.77 dB
Maximum RMS Power:	-6.09 dB	-6.06 dB
Average RMS Power:	-6.75 dB	-6.75 dB
Total RMS Power:	-6.75 dB	-6.75 dB
Actual Bit Depth:	16 Bits	16 Bits
(RMS Window = 50 ms)		

Vibrational Stimulus

Experiment 1 consisted of triangle wave driven vibrational FF periodicities as emitted by the joystick and triggered by the software program. The vibrational periodicities utilized what were termed to be: 10k, 15k, 30k, 45k, and 90k vibrational cycle periods. The periodicity of a force-feedback vibration is the *completion time* for one cycle of the vibration. Thus, it is essentially the opposite of audio frequency whereby the term frequency refers to how ‘frequently’ a full wave cycle occurs in one second. For periodicities in force-feedback, the term ‘period’ refers to the duration of its cycle as measured in microseconds. In this case for example, the 90k vibrational period would be .09 seconds (90/1000 of a second, thus the ‘90k’ name) for the completion of one cycle, and the 15k period would be .015 seconds, with the 90k period having a longer duration and therefore being a much slower cycle and thus a more deliberate and stronger feeling vibration. The reasoning for selecting the vibrational periodicities used was that of contrast—a 10k vibrational periodicity was a very ‘fine’ vibration in contrast to a 15k periodicity, and a 15k vibration would likewise was a ’fine’ vibration in contrast to 30k, but would be more ‘coarse’ or deliberate as compared to 10k. Thus the reasoning is to develop a range of periodicities that would differentiate from one another rather easily. The magnitude of periodic force-feedback vibrations ranges from 0 (no force) through 10,000 and are linear with a magnitude of 10,000 being twice that of 5,000. The horizontal axis represents the duration of an effect and the vertical axis the magnitude (Microsoft.com-MSDN, 2004). The vibration magnitude for all FF periodicities was constant at 10,000 (the maximum setting) for all trials, and all period durations were set at 20,000 which in milliseconds translates into a two second effect duration. Figure 5 presents a detailed example of a saw tooth wave periodic effect.

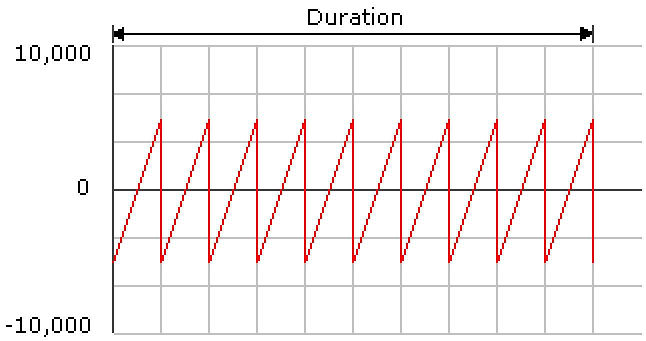
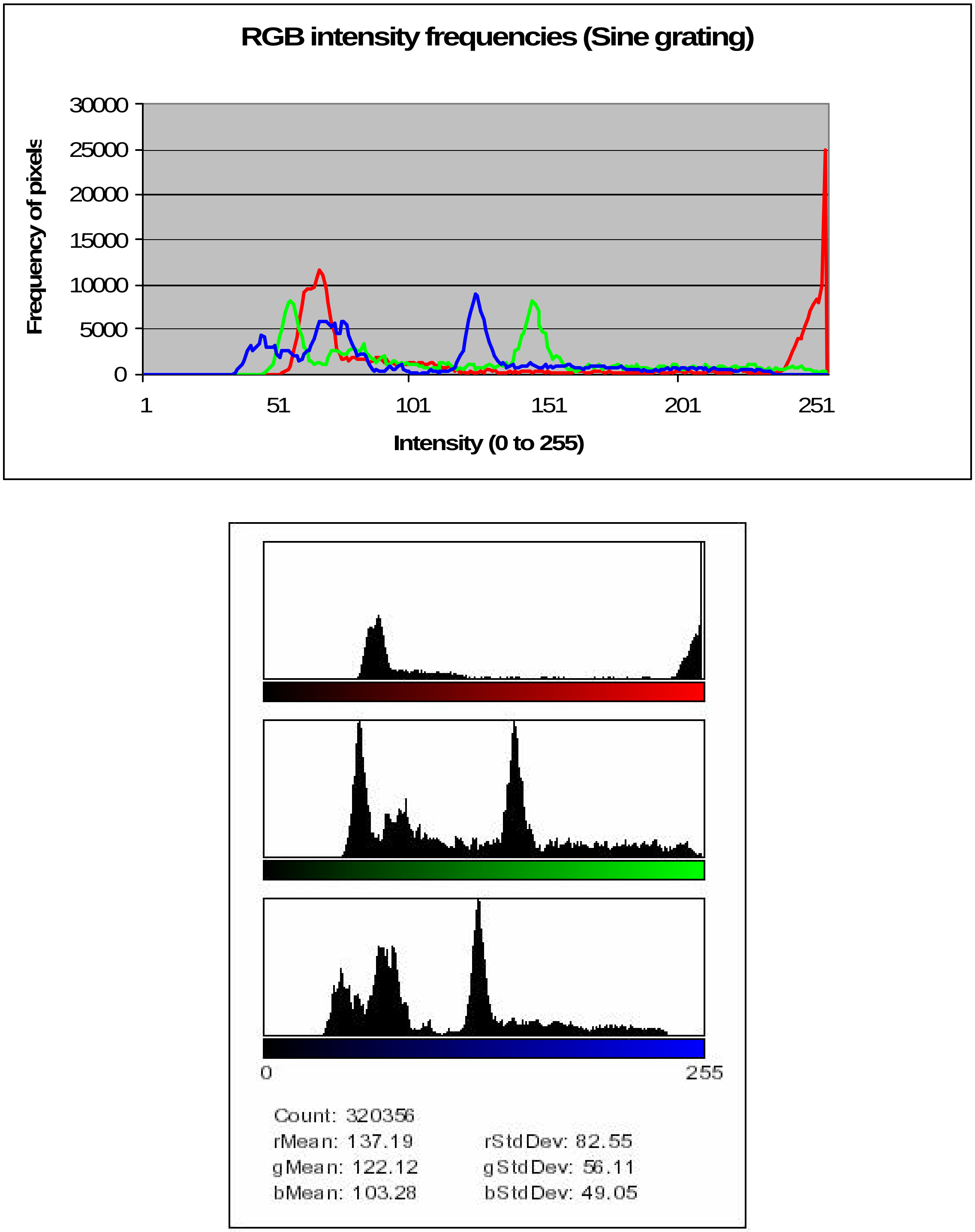


Figure 5. Sawtooth periodic effect with magnitude of 5,000; points above center line represent positive force in the direction defined for the effect; points below center line represent negative force, or force in the opposite direction (Miscosoft.com-MSDN, 2004).

Visual Stimulus

The visual stimulus for Experiment 1 was an image that contained the colors of visible light spectrum ROYGBIV. The stimulus was comprised of a "color-picker" image of continuous sinusoidal color gradations that matched the natural prismatic decomposition of visible spectrum light wavelengths (a "rainbow"), and is similar to a color-picker that one would find in a computer program for designing graphics. Figure 4 presents this color-picker as incorporated within the program interface. Participants would make color choices during trials by simply clicking directly on the color-picker image. In addition to providing basic color-choice derivation, the gradations of the color-picker image allowed for slightly differing blended hues to be selected. Actual dimensions of the color-picker on the computer screen were 145mm in width by 145mm in height. The color-picker was located in the upper left-hand corner of the screen, 12mm from the top, 16mm from the left, 175mm from the right, and 117mm from the bottom.

In order to gather responses that would reflect a high-level of sensitivity for 'blended' hue color gradations on the color picker image (e.g., yellowish-green, reddish-orange), horizontal 'X' axis, and vertical 'Y' axis coordinate values (represented in 'twips' with 1,440 twips per linear inch) as generated by the Microsoft Windows API (Applications Programming Interface) as they occurred when the cursor was moved across the color-picker image, were captured and subsequently recorded (additionally, there are 15 twips per pixel, and 96 pixels per inch). Requiring participants to define the position of the borders that divided colors as per the color-picker allowed the 'X' horizontal axis values to be representative of the ROYGBIV colors from left to right across the image. Thus, a color chosen by a participant could be defined by its 'X' value—a value that not only could represent a color specifically, but due to the fact that each color had inter-color variability, actual insight into 'blended' color choice response as aforementioned, could be analyzed as well. The actual Red, Green, Blue (RGB) pixel frequency distribution as a function of color intensity was analyzed using ImageJ image analysis program (Rasband, 2005). The sinusoidal grating color-picker RGB intensities histogram can be seen in Figure 6.



```
Count: 320356
rMean: 137.19          rStdDev: 82.55
gMean: 122.12          gStdDev: 56.11
bMean: 103.28          bStdDev: 49.05
```

Figure 6. Experiments 1-3 visual stimulus sinusoidal wave grating pixel frequency as a function of RGB intensity

The cycles-per-degree (CPD) spatial frequency for the sinusoidal visual stimulus was calculated using the participant color-picker dividing task. The color-dividing task provided mean 'twip' values for the vertical position of each of the six dividing lines placed between the seven ROYGBIV colors on the color-picker within Experiment 1 (Table 2).

TABLE 2

DESCRIPTIVE STATISTICS INCLUDING 'MEAN TWIP VALUES' GENERATED ON EXPERIMENT 1 COLOR-PICKER COLOR-DIVIDING TASK

Dividing line	N	Minimum	Maximum	Mean	Std. Deviation
Red-orange	50	0	5685	1395	1014
Orange-yellow	50	1515	2460	1972.5	177
Yellow-green	50	2400	3525	2749.2	223
Green-blue	50	3375	4800	4382.7	285
Blue-indigo	50	4950	5955	5274.3	228
Indigo-violet	50	4635	6435	5897.1	327

An example of this color-dividing task and the positioning of these participant-derived mean twip value lines on the color picker can be seen using the Experiment 1 color-dividing means as mapped to the sinusoidal color-picker stimulus presented in Figure 7.

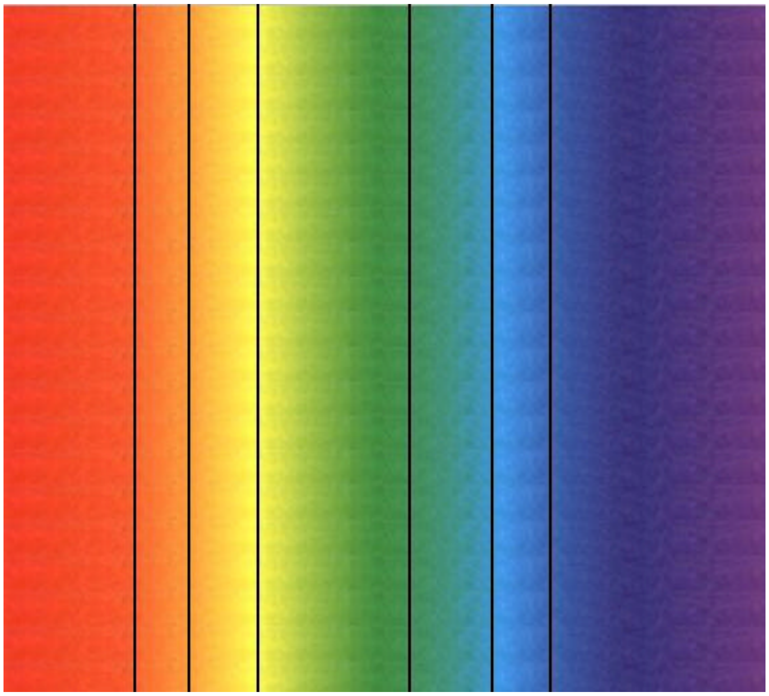
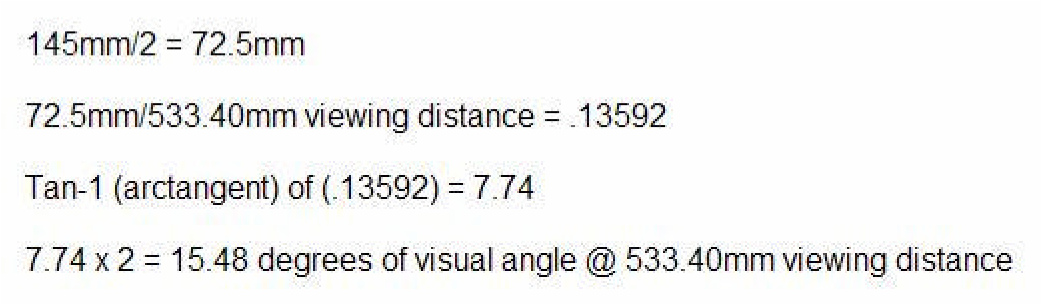


Figure 7. Positioning of participant defined color-dividing lines representing the Experiment 1 ‘mean twip values’ from Table 2

Overall size of the Experiment 1 visual stimulus contained .226 CPD based upon a spatial frequency of 3.5 cycles divided by 15.48 degrees of visual angle subtended by the color picker, the calculation of which can be seen in Figure 8.



145mm/2 = 72.5mm

72.5mm/533.40mm viewing distance = .13592

Tan-1 (arctangent) of (.13592) = 7.74

7.74 x 2 = 15.48 degrees of visual angle @ 533.40mm viewing distance

Figure 8. Calculated visual angle of overall stimulus 145mm height and 145mm width as subtended on retina for Experiments 1-3

This 15.48 degree visual angle was calculated with respect to the seating position for participants using the distance from the exact center of the visual stimulus on-screen to the author’s eye position as per author’s physical stature while in the seated position.

It is important to emphasize that the black lines placed on the color-picker during the color dividing task were not present on the stimulus when trials were underway. The lines disappeared when participants exited the color-dividing stage and proceeded to the experiment trials. It is also important to add that the color-dividing task provided the means by which to calculate the visual angle subtended by *each individual ROYGBIV area of color* (Appendix A) for these participant-defined widths such as those seen in Figure 7. Table 3 contains the Experiment 1 participant defined widths as converted to millimeters for visual angle calculation. The visual angle calculations for the Experiment 1 visual stimulus are contained within Appendix A.

TABLE 3

EXPERIMENT 1 PARTICIPANT-DEFINED COLOR WIDTHS AS CONVERTED FROM ‘TWIPS’ TO MILLIMETERS

Color	Defined width
Red	24.83mm
Orange	10.27mm
Yellow	13.83mm
Green	29.07mm
Blue	15.88mm
Indigo	11.09mm
Violet	39.99mm
Total	144.96 mm

It is important to add that in order to aid in the generalization of results, and acknowledging the fact that one would rarely find oneself in an isoluminant environment while feeling vibrations, the color-picker stimulus was not neutralized for presentation of equal “perceived brightness” (albedo), thus allowing colors perceived as brighter (e.g., yellow) to be perceived as such.

Procedure

The actual process of positioning participants to complete the task was comprised of several brief instructional phases. First, participants entered the lab and were seated at the first available workstation and read and signed a consent form, after which the experimenter started the computer program demographics information screen. Second, the crate with the joystick sitting on top of it was placed in front of the participants’ legs, and they were then instructed to move their chair forward while placing one leg on each side of the crate. They were assisted in positioning themselves closer to the table so as to assure that the crate and joystick were under the table where they were not able to have a direct line of sight with the joystick. They were then told to place their left hand on the joystick, and their right hand on the mouse, and that this would be the position that they would assume when participating in the stimulus trials. Participants were then told that this position was necessary so as to prevent them from having visual contact/feedback with/from their hand and the joystick during trials. Next, they were instructed that they would be wearing headphones during the trials and listening to white noise so as to give all participants an identical hearing experience during the experiment. Participants were told that the white noise would be similar to a constant whooshing sound like television static noise when a television is not tuned to any station. Participants were in the presence of an external volume control should the volume for some reason be too intense for them and they needed to adjust it. After the positioning instructions, the experimenter then told participants that all they needed to do was to put on the headphones, complete the demographics information to the best of their ability, click the ‘submit’ button, and then begin reading the instructions. The specific instructions for task participation as conveyed to all participants can be seen in Appendix B. Participants were told the task would last approximately 15-20 minutes.

As mentioned earlier, the software program presented to users was itself comprised of sections: the demographic information phase, the instruction phase, the ‘color-defining’ phase (only within conditions using the sinusoidal spatial frequency visual stimulus), the experimental trials phase, and the completion/debriefing phase. The instruction phase, following submission of demographics information, presented a screen where participants read instructions regarding the task. During the color-defining phase, a phase that was unique to all conditions that presented the sinusoidal grating ‘rainbow’ type of visual stimulus, participants were sequentially prompted by the program to choose the dividing lines between the various colors of a color picker (ROYGBIV) as seen earlier within the screenshot of the full interface presented in Figure 4. Participants were to define the area for a color by clicking on the color-picker at the location where they thought a “dividing-line” between any two colors should be placed (e.g., a dividing line between yellow and green). Upon clicking the color-picker image, a vertical black line would be placed on the color-picker. This would be placed wherever the participant clicked, and when a participant was satisfied with the positioning they had decided upon for the vertical line, they simply clicked the ‘continue’ button which would “anchor” the line and subsequently ask them complete the process again for a new line in order to define the next color in the sequence. After all six borderlines were defined in this manner for all ROYGBIV colors, the black lines on the color-picker image would disappear leaving the image in its normal state and participants began the actual stimulus trials of the experiment.

Trials were comprised of 10k, 15k, 30k, 45k, and 90k randomly ordered vibrational periodicities of two seconds in duration. Each stimulus played 10 times across the trial sequence with the first 5 trials being a predetermined non-random practice presentation of each of the five stimuli, so as to create an acclimation to stimulus expectancy and to facilitate familiarity with the general procedure. Thus, there were a total of 55 trials presented over the duration of the task. Participants were to simply click on area of the color-picker image that they thought was best associated with the vibration that they had experienced in their hand as conveyed by the joystick.

Results

Data Analysis

Of primary interest was the equality of proportions frequency distribution of color choices with respect to the five vibrational periodicities. However, due to the unequal distribution of participant-defined widths for each color across the visual stimulus (Figure 7, Table 3) it was first necessary to calculate a ‘weighted percentage values’ for each color, and then multiply all color-choice frequency counts by their respective weighted percentage values so as to give each color an equivalent representation within the analysis. These weighted percentage values for each color were created by 1) taking a value of 100% and dividing by 7 to calculate an equivalently distributed percentage value that each of 7 colors should have on the color stimulus— the value of which is 14.2857% (Table 4 column 3); 2) dividing each mean participant defined color width from Table 3 by the overall width of the stimulus (145mm), in order to calculate an ‘actual percentage value’ derived from each participant-defined mean color width (Table 4 column 4); 3) calculating ‘difference percentage values’ by subtracting 14.2857% from each aforementioned actual percentage value for each color (Table 4 column 5); 4) adding these ‘difference values’ (regardless of their valence value) to the value of 14.2857% once again, which created a final ‘weighted percentage’ value (Table 4 column 6).

A Chi Square analysis was then conducted for all vibrational periodicities and participant rendered color choices on experimental trials so as to reveal any potential significance in observed vs. expected frequencies. The Experiment 1 vibrational periodicities all yielded significant results from the analyses. The 10k vibrational periodicities, ?^{2} (6) = 25.83, *p* = .000239 and the 30k vibrational periodicities, ?^{2} (6) = 27.68, *p* = .000108 were both significant for the color blue, and the 15k vibrational periodicities, ?^{2} (6) = 27.94, *p* = 9.63E-05 were significant for the color yellow. The 45k vibrational periodicities, ?^{2} (6) = 17.03, p = .009166, and the 90k vibrational periodicities ?^{2} (6) = 24.87, p = .000361, were significant for the colors orange and red respectively. Actual observed frequencies can be seen in Table 5, with Table 6 presenting the Experiment 1 ‘weighted-expected’ equal distribution of color choice frequencies for all color choice associations. Table 7 shows the ‘weighted-observed’ frequency counts and indicates significant color-associations. Table 8 provides the Experiment 1 Chi Square statistics and significance levels as calculated from the weighted frequency counts. It is important to note that although post-weighting frequency counts on occasion do fall below 5 per cell for the Chi Square analysis, these weightings are derived from actual observed frequency counts that robustly surpass a value of 5 per cell.

TABLE 4

EXPERIMENT 1 ‘WEIGHTED PERCENTAGE VALUES’ CALCULATED FOR EACH COLOR AS DERIVED FROM PARTICIPANT-DEFINED COLOR WIDTHS

Color	Participant defined width in mm	Equal %	Participant defined %	Difference %	Weighted %
Red	24.83	0.142857	0.171	-0.0284	0.1145
Orange	10.27	0.142857	0.071	0.0720	0.2149
Yellow	13.83	0.142857	0.095	0.0475	0.1903
Green	29.07	0.142857	0.200	-0.0576	0.0852
Blue	15.88	0.142857	0.110	0.0333	0.1762
Indigo	11.09	0.142857	0.076	0.0664	0.2092
Violet	39.99	0.142857	0.276	-0.1329	0.0099
Total	144.96	0.999999	1.000		1.000

TABLE 5

EXPERIMENT 1 ACTUAL ‘OBSERVED’ FREQUENCY COUNTS FOR ALL COLOR ASSOCIATIONS WITH TRIANGLE WAVE DRIVEN VIBRATIONAL PERIODICITIES.

	10k	**15k**	**30k**	**45k**	**90k**	**Total**
Red	33	40	38	48	170	329
Orange	36	35	40	66	54	231
Yellow	88	96	69	70	27	350
Green	125	110	191	155	48	629
Blue	101	102	101	66	34	404
Indigo	43	39	28	34	37	181
Violet	74	78	33	61	130	376
Total	500	500	500	500	500	2500

TABLE 6

EXPERIMENT 1 ‘WEIGHTED-EXPECTED’ FREQUENCY COUNTS FOR ALL ROYGBIV COLOR STIMULUS ASSOCIATIONS WITH TRIANGLE WAVE DRIVEN VIBRATIONAL PERIODICITIES.

	10k	**15k**	**30k**	**45k**	**90k**	**Total**
Red	9.148	9.148	9.148	9.148	9.148	45.74
Orange	9.148	9.148	9.148	9.148	9.148	45.74
Yellow	9.148	9.148	9.148	9.148	9.148	45.74
Green	9.148	9.148	9.148	9.148	9.148	45.74
Blue	9.148	9.148	9.148	9.148	9.148	45.74
Indigo	9.148	9.148	9.148	9.148	9.148	45.74
Violet	9.148	9.148	9.148	9.148	9.148	45.74
Total	64.036	64.036	64.036	64.036	64.036	320.18

TABLE 7

EXPERIMENT 1 ‘WEIGHTED-OBSERVED’ FREQUENCY COUNTS FOR ALL COLOR ASSOCIATIONS WITH TRIANGLE WAVE DRIVEN VIBRATIONAL PERIODICITIES.

	10k	**15k**	**30k**	**45k**	**90k**	**Total**
Red	3.775	4.576	4.347	5.491	19.448	37.638
Orange	7.733	7.518	8.592	14.177	11.599	49.619
Yellow	16.746	18.269	13.131	13.321	5.138	66.605
Green	10.650	9.372	16.273	13.206	4.090	53.591
Blue	17.786	17.962	17.786	11.623	5.987	71.144
Indigo	8.996	8.159	5.858	7.113	7.740	37.865
Violet	0.733	0.772	0.327	0.604	1.287	3.722
Total	66.4187	66.628	66.3135	65.5343	55.2897	320.1842

TABLE 8

EXPERIMENT 1 CHI SQUARE STATISTICS AND SIGNIFICANCE VALUES FOR THE ‘WEIGHTED-OBSERVED’ FREQUENCY COUNTS

	p	***X2:***
10k	0.000239	**25.83**
15k	9.63E-05	**27.94**
30k	0.000108	**27.68**
45k	0.009166	**17.03**
90k	0.000361	**24.87**

Discussion

These results clearly indicate that participant color-association varies with respect to the vibrational periodicity accompanying a triangle waveform. However, upon closer inspection one needs to consider the actual strength of such color associations—particularly with respect to evidence as seen within the 15k vibration results. Here the color of choice was yellow—a momentary deviation from the color blue as garnered by the 10k vibrational periodicities. Most interestingly, the pattern of color association subsequently returned to blue once again within the trials for the 30k vibrational periodicities. A close inspection of the actual observed frequencies shows that this departure for the yellow color associations on the 15k periodicities was in fact a function of the 'weighting-percentage' as applied to the actual observed frequencies and thus did not actually result independent of the application of the weighting methodology. As per the naturally observed actual frequency counts, the color association of the 10k through 45k vibration periodicites arrive at the color green with respect to frequency counts—only the 90k periodicities remain constant with respect to their association with the color red on both the observed frequency counts and the weighted-observed frequency counts.

Perhaps it should be noted that although the adjustment of the color stimulus via weighted percentages for each color seems a reasonable adjustment due to the natural representation of the colors on the sinusoidal stimulus, the actual electromagnetic spectrum bandwidth for visible light and the colors it represents is itself not equally distributed percentage-wise across the spectrum.

CHAPTER IV

EXPERIMENT 2

Experiment 2 incorporated a square wave driven vibrational stimulus within the design, so as to test any potential differences between the Experiment 1 triangle waveform driven vibration vs. a square wave driven vibration, with respect to color choice on the sinusoidal waveform color-picker stimulus.

Method

Participants

Forty-nine graduate and undergraduate students (38 female, 11 male) from Wichita State University participated and received partial course credit for their participation.

Materials

The study was again completely self-contained using a program written with Microsoft Visual Basic 6.0. The program presented the same experimental sequence that consisted of 1) demographic information collection, 2) instructions to participants, 3) Color-defining phase, 4) experimental stimulus trials, 5) completion screen, and 6) debriefing information.

Equipment and apparatus

Computers and apparatus utilized were the exact same as those used within Experiment 1. Participants were also placed in the exact same seated positioning for Experiment 2 as they were for experiment 1, and were again positioned so as not to be able to have any visual contact with the joystick in their hand. Participants once again had neutralized hearing via application of white noise from headphones.

Vibrational stimulus

The vibrational stimulus for Experiment 2 consisted of square wave driven vibrations. The same five vibrational periodicities were again utilized: 1k (.01 seconds/cycle), 15k (.015 seconds/cycle), 30k (.030 seconds/cycle), 45k (.045 seconds/cycle), and 90k (.09 seconds/cycle). Similarly, the representative cycle-times-per-vibration was identical to the first experiment, as was duration (2 seconds), and magnitude (10,000).

Visual stimulus

As it was in Experiment 1, the visual stimulus consisted of the same sinusoidal wave color-picker image ordered in the colors of the visible light spectrum ROYGBIV (Figure 4). The Experiment 2 color-dividing task prior to trials was the same as that in Experiment 1 and thus provided an identical method by which participants could provide absolute definitive borders for specific colors (Figure 9).

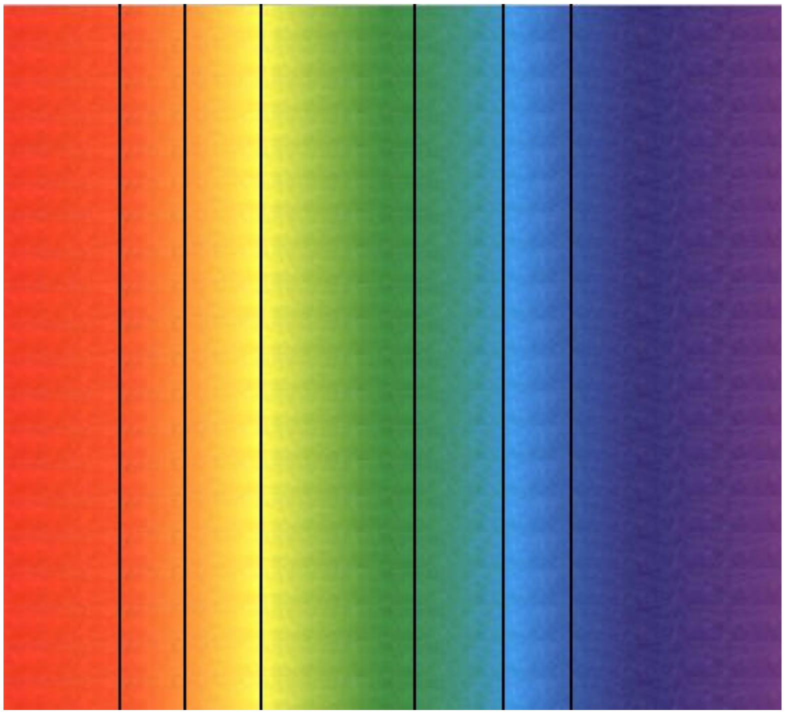


Figure 9. Positioning of participant defined color-dividing lines representing the Experiment 2 ‘mean twip values’ in Table 9

As was mentioned in Experiment 1, this color-dividing task provided mean ‘twip’ values for the vertical position of each of the six dividing lines placed between the seven ROYGBIV colors on the color-picker within Experiment 2 (Table 9). The millimeter conversion values of these Experiment 2 derived ‘mean twip values’ is presented in Table 10.

TABLE 9

DESCRIPTIVE STATISTICS INCLUDING ‘MEAN TWIP VALUES’ GENERATED ON EXPERIMENT 2 COLOR-PICKER COLOR-DIVIDING TASK

Dividing line	N	Minimum	Maximum	Mean	Std. Deviation
Red-orange	49	135	3525	1228.163	511.043
Orange-yellow	49	1200	2700	1943.265	242.063
Yellow-green	49	2490	3330	2758.469	179.615
Green-blue	49	3930	4800	4365.306	195.324
Blue-indigo	49	4980	6165	5278.163	243.637
Indigo-violet	49	5490	6885	5991.735	322.443

TABLE 10

EXPERIMENT 2 PARTICIPANT-DEFINED COLOR WIDTHS AS CONVERTED FROM ‘TWIPS’ TO MILLIMETERS

Color	Defined width
Red	21.89mm
Orange	12.73mm
Yellow	14.52mm
Green	28.61mm
Blue	16.25mm
Indigo	12.71mm
Violet	38.31mm
Total	145.0mm

Identical to the first experiment, participants made color choices during trials by clicking directly on the color-picker image, after which the exact X an Y vertical and horizontal axis positions in twip values of the cursor upon the image would be recorded along with the color that the XY positions represented. Cycles-per-degree (CPD) spatial frequency for the sinusoidal visual stimulus was also identical to that of the first experiment.

Procedure

The procedure by which participants were guided through the instructional phase and participant navigation of the actual experimental procedure itself was identical to that of Experiment 1.

Results

Data analysis

Once again the primary analyses of interest were those of Chi Square equality of proportions for frequency distribution of color choice associations. However, the results from Experiment 2 were unusual above and beyond the level of interest generated by the Experiment 1 analyses. The 10k vibrational periodicities, ?^{2} (6) = 40.50, *p* = 3.63E-07, and the 15k vibrational periodicities, ?^{2} (6) = 31.99, *p* = 1.64E-05 were significant for the color yellow. The 30k vibrational periodicities, ?^{2} (6) = 17.66, *p* = .0071 were significant for the color green, and the 90k vibrational periodicities, ?^{2} (6) = 16.93, *p* = .0095 were significant for the color red. The 45k vibrational periodicities did not garner significance for any color.

As one can see from the Experiment 1 triangle wave vibration group weighted-observed frequencies seen in Table 7 as compared with the Experiment 2 square wave vibration group weighted-observed frequencies in Table 14, there is a distinct color preference difference for the Experiment 1 triangle waveform vs. the square waveform vibrations. Table 13 contains the Experiment 2 weighted-expected frequencies and Table 15 contains the Experiment 2 square wave vibration group Chi Square statistics and significance values for the Table 14 weighted-observed frequencies.

TABLE 11

EXPERIMENT 2 ‘WEIGHTED PERCENTAGE VALUES’ CALCULATED FOR EACH COLOR AS DERIVED FROM PARTICIPANT-DEFINED COLOR WIDTHS

Color	Participant defined width in mm	Equal %	Participant defined %	Difference %	Weighted %
Red	21.89	0.142857	0.151	-0.0081	0.1347
Orange	12.73	0.142857	0.088	0.0551	0.1979
Yellow	14.52	0.142857	0.100	0.0427	0.1856
Green	28.61	0.142857	0.197	-0.0545	0.0884
Blue	16.25	0.142857	0.112	0.0308	0.1736
Indigo	12.71	0.142857	0.088	0.0552	0.1981
Violet	38.31	0.142857	0.264	-0.1213	0.0215
Total	145	0.999999	1.000		1.000

TABLE 12

EXPERIMENT 2 ‘ACTUAL-OBSERVED’ FREQUENCY COUNTS FOR ALL COLOR ASSOCIATIONS WITH SQUARE WAVE DRIVEN VIBRATIONAL PERIODICITIES.

	10k	**15k**	**30k**	**45k**	**90k**	**Total**
Red	34	32	33	76	125	300
Orange	46	46	53	55	42	242
Yellow	124	107	65	47	21	364
Green	120	142	177	93	45	577
Blue	99	94	75	43	31	342
Indigo	30	26	44	53	39	192
Violet	37	43	43	123	187	433
Total	490	490	490	490	490	2450

TABLE 13

EXPERIMENT 2 ‘WEIGHTED-EXPECTED’ FREQUENCY COUNTS FOR ALL COLOR ASSOCIATIONS WITH SQUARE WAVE DRIVEN VIBRATIONAL PERIODICITIES.

	10k	**15k**	**30k**	**45k**	**90k**	**Total**
Red	8.96	8.96	8.96	8.96	8.96	44.8
Orange	8.96	8.96	8.96	8.96	8.96	44.8
Yellow	8.96	8.96	8.96	8.96	8.96	44.8
Green	8.96	8.96	8.96	8.96	8.96	44.8
Blue	8.96	8.96	8.96	8.96	8.96	44.8
Indigo	8.96	8.96	8.96	8.96	8.96	44.8
Violet	8.96	8.96	8.96	8.96	8.96	44.8
Total	62.72	62.72	62.72	62.72	62.72	313.6

TABLE 14

EXPERIMENT 2 ‘WEIGHTED-OBSERVED’ FREQUENCY COUNTS FOR ALL COLOR ASSOCIATIONS WITH SQUARE WAVE DRIVEN VIBRATIONAL PERIODICITIES.

	10k	**15k**	**30k**	**45k**	**90k**	**Total**
Red	4.582	4.312	4.447	10.241	16.844	40.426
Orange	9.104	9.104	10.490	10.886	8.313	47.897
Yellow	23.012	19.857	12.063	8.722	3.897	67.553
Green	10.608	12.553	15.648	8.222	3.978	51.009
Blue	17.192	16.323	13.024	7.467	5.383	59.390
Indigo	5.942	5.150	8.715	10.497	7.724	38.028
Violet	0.796	0.925	0.925	2.646	4.023	9.316
Total	71.23658	68.22559	65.31113	58.68172	50.16326	313.6183

TABLE 15

EXPERIMENT 2 CHI SQUARE STATISTICS AND SIGNIFICANCE VALUES FOR THE ‘WEIGHTED-OBSERVED’ FREQUENCY COUNTS

	p	***X2:***
10k	3.63E-07	**40.50**
15k	1.64E-05	**31.99**
30k	0.007153	**17.66**
45k	0.466378	**5.63**
90k	0.009531	**16.93**

CHAPTER V

EXPERIMENT 3

Experiment 3 looked at the relationship between sinusoidal wave driven vibrational periodicities and the sinusoidal color-picker ROYGBIV stimulus.

Method

Participants

Forty-five graduate and undergraduate students (31 female, 14 male) from Wichita State University participated and received partial course credit for their participation.

Materials

As it was for Experiments 1 and 2, Experiment 3 was a self-contained using a program written with Microsoft Visual Basic 6.0., and presented an experimental sequence that consisted of 1) demographic information collection, 2) instructions to participants, 3) Color-defining phase, 4) experimental stimulus trials, 5) completion screen, and 6) debriefing information.

Equipment and apparatus

Computers and apparatus utilized were once again the identical machines as those in Experiment 1 and Experiment 2. Participants were tested at the same workstations as those for Experiment 1 and Experiment 2, were devoid of any visual contact with the joystick in their hand, and listened to white noise from headphones so as to control for extraneous sound exposure.

Vibrational stimulus

The vibrational stimulus for Experiment 3 consisted of sinusoidal wave driven vibrations, with the same five vibrational periodicities once again being utilized: 1k (.01 seconds/cycle), 15k (.015 seconds/cycle), 30k (.030 seconds/cycle), 45k (.045 seconds/cycle), and 90k (.09 seconds/cycle). The cycle-times-per-vibration was again identical to both previous experiments, as was periodicity duration (2 seconds), and vibrational magnitude (10,000).

Visual stimulus

The visual stimulus consisted of the same vertically oriented sinusoidal wave color-picker image representing the visible light spectrum colors ROYGBIV (Figure 4) as used for Experiments 1 & 2. Once again, a color-dividing task prior to trials to allow participants to derive definitive borders for specific colors (Figure 10), with participant color choices during trials providing exact X an Y vertical and horizontal axis positions in twip values of the cursor click upon the image.

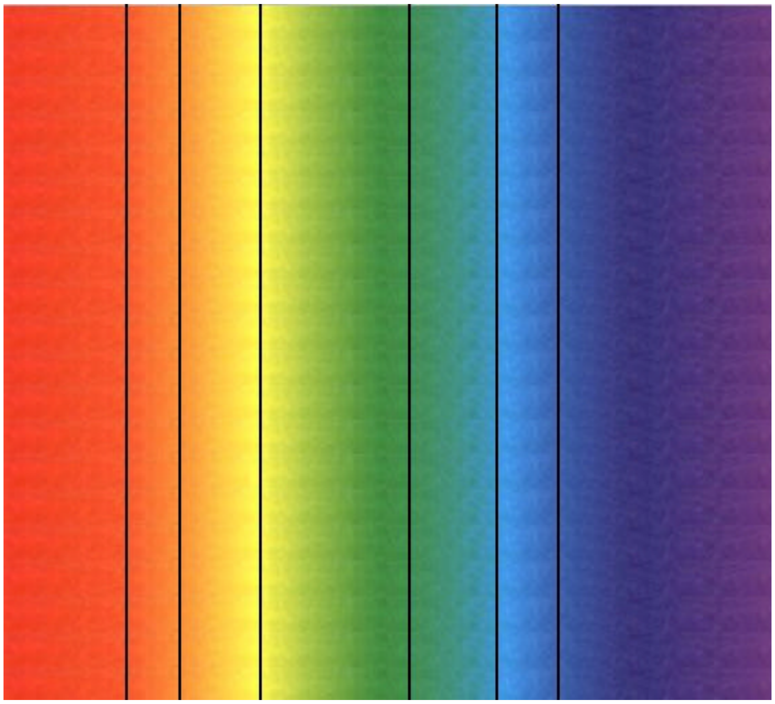


Figure 10. Positioning of participant defined color-dividing lines representing the Experiment 3 ‘mean twip values’ from Table 16

Descriptive statistics for these twip values can be seen in Table 16, and the millimeter conversion values for participant-defined color widths as derived from these twips can be seen in Table 17.

TABLE 16

DESCRIPTIVE STATISTICS INCLUDING ‘MEAN TWIP VALUES’ GENERATED ON EXPERIMENT 3 COLOR-PICKER COLOR-DIVIDING TASK

Dividing line	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Red-orange	45	465	2475	1304.667	361.2689
Orange-yellow	45	465	2355	1895	299.3174
Yellow-green	45	2520	3345	2767	187.6935
Green-blue	45	2610	4785	4351.333	340.146
Blue-indigo	45	4980	5910	5275.667	217.7379
Indigo-violet	45	5445	6855	5964	322.8471

TABLE 17

EXPERIMENT 3 PARTICIPANT-DEFINED COLOR WIDTHS AS CONVERTED FROM ‘TWIPS’ TO MILLIMETERS

Color	Defined width
Red	23.23mm
Orange	10.51mm
Yellow	15.52mm
Green	28.20mm
Blue	16.45mm
Indigo	12.25mm
Violet	38.8mm
Total	144.994 mm

All visual stimulus XY twip values were again recorded along with the color the XY positions represented. Cycles-per-degree (CPD) spatial frequency for the sinusoidal visual stimulus was again identical to that of the previous experiments.

Procedure

The instructional phase and the participant flow through the Experiment 3 sequence were identical to Experiments 1 & 2.

Results

Data analysis

Primary analyses of interest were once again Chi Square equality of proportions tests to highlight observed frequency distribution of participant color association choices with the five different vibrational periodicities presented. The Chi Square analyses did arrive at a significant result regarding the association of yellow with the 10k sinusoidal vibrational periodicities, ?^{2} (6) = 19.76, p = .003057, and the 15k vibrational periodicities, ?^{2} (6) = 22.44, p = .001006. The 30k vibrational periodicites, ?^{2} (6) = 17.05, p = .009085, were significant for the color blue, and the 90k vibrational periodicites were significant in association with the color red, ?^{2} (6) = 24.24, p = .000472. Identical to the Experiment 2 results, the 45k vibrational periodicities were once again the sole periodicity that did not yield a significant color association.

Weighted-observed frequencies for Experiment 3 color choices can be seen in Table 21. Table 20 presents the weighted-expected frequencies, and Table 22 the Chi Square statistics and associated probability values.

TABLE 18

EXPERIMENT 3 'WEIGHTED PERCENTAGE VALUES' CALCULATED FOR EACH COLOR AS DERIVED FROM PARTICIPANT-DEFINED COLOR WIDTHS

Color	Participant defined width in mm	Equal %	Participant defined %	Difference %	Weighted %
Red	23.23	0.142857	0.160	-0.0173	0.1255
Orange	10.51	0.142857	0.072	0.0704	0.2132
Yellow	15.52	0.142857	0.107	0.0358	0.1787
Green	28.2	0.142857	0.194	-0.0516	0.0912
Blue	16.45	0.142857	0.113	0.0294	0.1723
Indigo	12.25	0.142857	0.084	0.0584	0.2012
Violet	38.8	0.142857	0.268	-0.1247	0.0181
Total	144.96	0.999999	1.000		1.000

TABLE 19

EXPERIMENT 3 ‘ACTUAL-OBSERVED’ FREQUENCY COUNTS FOR ALL COLOR ASSOCIATIONS WITH SINUSOIDAL WAVE DRIVEN VIBRATIONAL PERIODICITIES.

	10k	**15k**	**30k**	**45k**	**90k**	**Total**
Red	47	37	42	69	158	353
Orange	19	31	32	41	28	151
Yellow	92	95	62	59	37	345
Green	109	123	126	109	63	530
Blue	74	79	93	57	38	341
Indigo	34	32	35	47	33	181
Violet	75	53	60	68	93	349
Total	450	450	450	450	450	2250

TABLE 20

EXPERIMENT 3 ‘WEIGHTED-EXPECTED’ FREQUENCY COUNTS FOR ALL COLOR ASSOCIATIONS WITH SINE WAVE DRIVEN VIBRATIONAL PERIODICITIES.

	10k	**15k**	**30k**	**45k**	**90k**	**Total**
Red	8.153	8.153	8.153	8.153	8.153	40.765
Orange	8.153	8.153	8.153	8.153	8.153	40.765
Yellow	8.153	8.153	8.153	8.153	8.153	40.765
Green	8.153	8.153	8.153	8.153	8.153	40.765
Blue	8.153	8.153	8.153	8.153	8.153	40.765
Indigo	8.153	8.153	8.153	8.153	8.153	40.765
Violet	8.153	8.153	8.153	8.153	8.153	40.765
Total	57.070	57.070	57.070	57.070	57.070	285.352

TABLE 21

EXPERIMENT 3 ‘WEIGHTED-OBSERVED’ FREQUENCY COUNTS FOR ALL COLOR ASSOCIATIONS WITH SINE WAVE DRIVEN VIBRATIONAL PERIODICITIES.

	10k	**15k**	**30k**	**45k**	**90k**	**Total**
Red	5.899	4.644	5.272	8.660	19.831	44.306
Orange	4.051	6.610	6.823	8.743	5.971	32.198
Yellow	16.439	16.975	11.078	10.542	6.611	61.646
Green	9.400	10.607	10.865	9.400	5.433	45.704
Blue	12.748	13.610	16.021	9.820	6.546	58.745
Indigo	6.842	6.439	7.043	9.458	6.641	36.423
Violet	1.360	0.961	1.088	1.233	1.686	6.329
Total	56.73932	59.84627	58.19168	57.85565	52.71941	285.352

TABLE 22

EXPERIMENT 3 SINUSOIDAL VIBRATION GROUP CHI SQUARE STATISTICS AND SIGNIFICANCE VALUES FOR ‘WEIGHTED-OBSERVED’ FREQUENCY COUNTS

	p	***X2:***
10k	0.003	**19.76**
15k	0.001	**22.44**
30k	0.009	**17.05**
45k	0.286	**7.39**
90k	0.000	**24.24**

Discussion

As it was within Experiments 1 & 2 there was definitive participant color association with presented vibrational periodicities. In addition, this provides the necessary insight indicating that the triangle wave driven vibrational periodicities for some reason garnered a unique color-association pattern as compared to the similar results seen in Experiments 2 and 3.

Perhaps most important was the fact that this particular experiment matched the *fundamental* waveform of a sinusoid head-to-head with respect to the waveform driving both the visual and the vibrational stimuli, and yet arrived at a nearly identical color-association result as that of Experiment 2.

GENERAL DISCUSSION

The fact that the Experiment 2 and Experiment 3 results were nearly identical is not that surprising when one considers the fact that all waveforms are comprised of a number of sinusoidal waveforms. The decomposition of complex as well as simple waveforms into their constituent sinusoidal components can be achieved via Fourier analysis whereby any periodic function can be represented as the sum of its sinusoidal components (Mastascusa, 2006). However, this anomaly emphasizes the results of Experiment 1 all the more—with all experiments having the same basic fundamental sinusoidal building blocks for their vibrations and visual stimuli, what might have caused the color-association disparity between Experiments 2 & 3 vs. Experiment 1?

The possibility exists that participants have associated vibrations that have certain types of transitional points from waveform peak to valley—such as the abrupt transition of a square wave—with colors that are known to be subjectively interpreted as 'cooler' or 'harder' colors, such as violet and blue (Van Wagner, 2006). Conversely, the colors that are subjectively known to be 'softer' colors, such as red, yellow, and orange are perhaps associated with less distinct and smoother transition waveforms such as those of the sinusoidal and triangle waveforms. Additionally, one must not forget the differences in harmonic content that different waveforms possess and how the presence/absence of certain harmonic content might influence the results as seen. Table 23 provides the differences in harmonic content for triangle, square, and sinusoidal waveforms.

TABLE 23

WAVEFORM HARMONIC CONTENT FOR TRIANGLE, SQUARE, AND SINE WAVES

Waveform	**Harmonic content**
Triangle	Odd harmonics only
Square	Odd harmonics only
Sine	No harmonics

The harmonic content of triangle and square waves is similar in that they contain only odd harmonics—albeit the high harmonics of the triangle wave drop off faster than do square wave harmonics and thus the triangle wave has a smoother sound that is more similar to sine waves (Wikipedia.org, 2007). Sine waves on the other hand are completely lacking in harmonic content. This makes the similar results of Experiments 2 & 3 all the more interesting in that their base waveforms consisted of disparate harmonic content, and yet arrived at similar results. The harmonic content of Experiments 1 & 2 was odd harmonic content only, and yet the color-association results of these two experiments were also incongruent. The indication is that harmonic content is not a primary influence in such associations with respect to the experimental paradigm as presented. The best explanation may be that the peak amplitude and the ramp-up to the peak amplitude for each cycle of the square wave (Experiment 2) and the sine wave (Experiment 2) vibrations was similar enough to have them garner similar color-associations despite their extreme differences—and particularly so when one remembers that the ramp-up to peak amplitude for a triangle wave cycle is more similar to a sinusoidal wave than it is to a square wave.

Clearly there is some type of uniquely specific physiological cross-modal processing that is being revealed with respect to visual response to the color stimulus and the processing of the vibrational information via mechanoreceptor Pacinian corpuscles and muscle spindles. It is these mechanoreceptors in the skin that are most likely to have involvement in such a systematic response being that the Pacinian corpuscles are pressure receptors that encode the frequency of impulses regarding the magnitude of a stimulus once its threshold is reached—and the muscle spindles responding to any 'stretching' of their fibers and sending information about position of the muscles, bones, and joints (Kimball, 2003). In addition, once cannot exclude the fact that the contraction of muscles derived from an active grasping may make muscle spindles mores sensitive to high-frequency vibrations (Brisben, Hsiao, & Johnson, 1999). Given the complexity of the hand with respect to the number of joints and bones, it is likely there is a collaboration of the involved mechanoreceptors. This might be particularly so in the case of a strong, slow, and deliberate vibration such as the periodic cycle of the 90k vibration as presented during trials—a vibration slow enough to register muscles spindle activity strongly, and yet rapid enough to register mechanoreceptor activity strongly as well.

It is important to develop discussion insight into tactile processing areas such as the mechanoreceptors and then lead into visual-processing, so as to attempt to determine commonality of neurons/neural pathway regarding the cross-modality processing results as represented within the data. With respect to brain processing areas for active and passive touch, the S1 cortex or 'primary somatosensory cortex' area has cortical neuronal activity during movements, with a pattern of discharge for both the deep and cutaneous receptors most likely mirroring feedback from peripheral mechanoreceptor activation rendered during the course of the movements (Chapman, Tremblay, & Ageranioti-Belanger, 1996). Therefore the relevant route to take for an assessment of this unusual cross-modality processing would likely involve S1 afferent and efferent pathways and any sub-processing domains, and how they may in some way 'share' resources or pathways with the visual cortex.

Goldstein (2002) indicates that most of the nerve fibers from receptors in the skin travel via two pathways, the medial lemniscal pathway and the spinothalamic pathway—with most of the fibers synapsing in the ventral posterior nucleus in the thalamus. Most importantly, nerve fibers from the retina also synapse in the thalamus at the area of the lateral geniculate nucleus. Being that the thalamus relays information from the diversity of brain regions to the cerebral cortex it is a required 'last pit stop' of sorts for the dissemination of information. Axons from all sensory systems (save for Olfactory) synapse in the thalamus as a last relay site before information reaches the cortex (White, DeSantis, Laskowski, & McKean, 2005). It would appear that this is the first logical center whereby the two processing pathways could have cross-modal processing commonality via some thalamic junction point. It would also seem unlikely that any cross-modality processing would occur at the end-of-the-line per se—that is, within the occipital lobe for instance. Being that this is a specialized visual processing area of the cortex it is unlikely that proprioceptive or tactile vibrational information is processed here.

The different types of haptic-touch receptors of the human hand, and their potential contribution to the results of this investigation, should be brought to light as well. Table 24 presents the various mechanoreceptor types and the vibrational frequency response-range for each type.

TABLE 24

PROPERTIES OF MECHANORECEPTORS OF THE SKIN (GOLDSTEIN, 2002)

Receptor	**Frequency Range**	**Perception**
Merkel	0.3—3 Hz (slow pushing)	Pressure
Meissner	3—40 Hz	Flutter
Ruffini	15—400 Hz	Stretching
Pacinian	10—500 Hz	Vibration

It should be noted that the Meissner, Ruffini, and the earlier mentioned Pacinian mechanoreceptor types as seen in Table 24, all possess a frequency range that includes frequencies for vibrational periodicities as presented in this experiment. Table 25 provides the frequency conversions of the vibrational periodicites as used in the current study.

TABLE 25

EXPERIMENTS 1-3 VIBRATIONAL PERIODICITIES CONVERTED TO FREQUENCY IN HERTZ (HZ)

Vibration periodicity	**Elapsed time for 1 cycle**	**Frequency in Hz**
10k	10/1000 second	1000 Hz
15k	15/1000 second	66.666 Hz
30k	30/1000 second	33.333 Hz
45k	45/1000 second	22.222 Hz
90k	90/1000 second	11.111 Hz

In looking at the Table 25 frequency conversions along with the Table 24 mechanoreceptor frequency ranges it becomes clear that the possibility of specific vibrations, such as the 90k periodicities, were in fact causing differential color-association results due to the fact that they were reflecting motion-related perceptive response information such as ‘flutter’, rather than frequency-related information. One can clarify this a bit further by pointing out how both the Pacinian and Meissner receptor ranges can both account for responses to a frequency of 11.111 Hz—the frequency of the 90k vibration periodicities. It seems a bit more logical that the Meissner receptor would be the receptor involved with the 90k periodicities being that the frequency range of the Meissner (3-40 Hz) is more compact and appears more specialized for slower, more deliberate vibrational frequencies than does the more globally sensitive Pacinian receptor (10-500 Hz). One cannot dispute the fact that consistency in the results does exist with the slow, deliberate 90k vibrational periodicites—as evidenced by the red color association significant results garnered by Experiments 1-3 independent of the waveform type driving the periodicities. Perhaps, only future research via isolating vibration presentations within more controlled frequency ranges would clarify this unusual result any further.

One of the most significant bodies of research contested by the results of the current study is that of Graziano and Gross (1995) who found bimodal neurons in the cortex that respond to both visual and tactile stimuli. By studying Rhesus monkeys and bimodal cell neural responses, they found that if a monkey’s hand was visually accessible to them (Figures 11a and 11b), these specialized neurons responded to both tactile and visual stimulation—if the hand was not visible, these cells would only respond to tactile stimulation alone (Figure 11c).

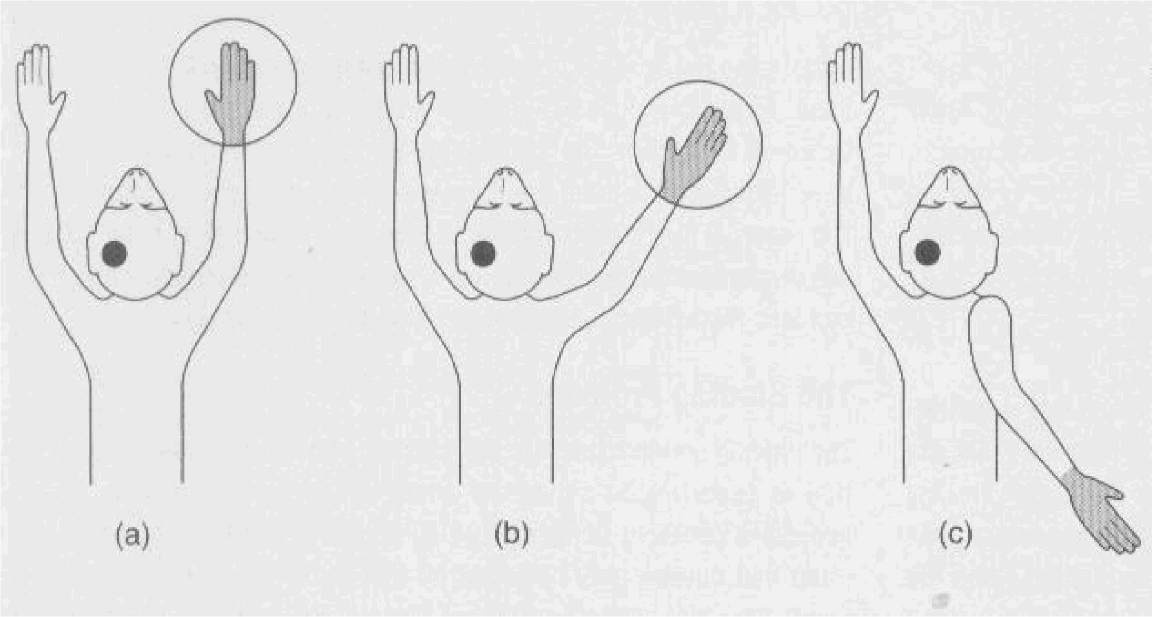


Figure 11. Bimodal cell response to simultaneous visual and tactile stimulus is dependent on visual field presence of the hand (Goldstein, 2002, p.139)

This is a stark contrast to the current study results whereby participants had no visual contact with their hand while receiving FF vibrations, and yet they responded to tactile vibrational periodicities during natural 'rainbow-ordered' ROYGBIV sinusoidal color visual stimulus presentations, with systematic color-choices significance levels that are highly conclusive. The results of the current study seemingly indicate that visibility of the hand is a *sufficient* condition to cause bimodal neural activation, but not a *necessary* condition for such activation to occur. Graziano and Gross indicate visual-tactile neurons are present in inferior area 6 of the frontal lobe, parietal lobe area 7b, and the putamen, with their tactile receptive fields arranged to form a somatotopic map, and the visual receptive fields as usually being adjacent to the tactile ones and extending outward from the skin approximately 20cm. Therefore each of these areas contains an organized somatotopic map of the visual space that immediately surrounds the body. For many neurons with tactile receptive fields on the arm or the hand, this type of organization fosters visual receptive field movement when the arm is moved.

It is hypothesized with respect to the unusual results of the current study, that the sinusoidal-waveform is perhaps a primary building-block of nature with respect to the cross-modal experiencing of such psychologically subjective percepts as a naturally ordered visible color spectrum stimulus with tactile sensations—and that such sinusoidal presentations maximize the number of neural cortex firings and shared information across sensory modalities for any single or combined cross-modal human sensory opportunity, resulting in a stronger more definitive perceptual experience.

As was mentioned at the beginning of the paper, the study by Ye, Corso, Hager, and Okamura (2003) can perhaps be related back to this study by mentioning that the crate on which the joystick rested may well have interfered with the purity of transfer of the vibrational stimuli—perhaps the colors yellow or orange require a more pure experience of the vibrational transfer and this apparatus diluted that purity of experience.

It must be added that participants were not screened for vision difficulties such as color blindness—a deficit that could clearly affect the response quality of some individuals. Similarly, it could have been beneficial to question participants on any neuromotor difficulties they may have had being that any such deficits in the left hand, or damage to nerve tissue in the left arm or hand, may have contributed adversely to the quality of the participant responses. Ultimately, the results remain profound and significant and each group sample size itself appears to have absorbed any differences that may have existed within individuals.

GENERAL CONCLUSIONS

Other research lines extending from these findings should be carried out in the future as their potential to provide greater insight into bi-modal neural processing in the face of cross-modal stimulus presentations is of paramount importance. In addition, other types of analyses, such as those using classification methodologies, could be used in an attempt to create a model for predicting group membership (such as age or gender) with respect to the differing periodicities and their associated color choices. The nature of the relationship as tested in this experiment can by no means be defined without further in-depth studies to include neurological/physiological mechanisms that may be involved.

However, the present study does provide a good foundation and a solid base from which to build a more refined line of research. The development of this relationship between haptic vibration and color perception is still in its infancy, but it takes little imagination for one to arrive at the notion that it could have a huge impact on multimedia software, portable communications, virtual reality, and the future of innovative high-quality sensory experiences on a global basis.

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APPENDICES

APPENDIX A

EXPERIMENTS 1-3 VISUAL ANGLE CALCULATIONS

Generalities:

1,440 twips per inch
56.1622 twips per mm
1mm = .039 inches
25.64mm per inch
533.40mm viewing distance = 20.8 inches

Experiment 1-3 visual stimulus dimensions:
Overall width & height = 145mm x 145mm

Experiments 1-3 visual angle calculation for overall height & width of color-picker stimulus:
(Entire stimulus height & width = 145mm x 145mm)
145mm/2 = 72.5mm
72.5mm/533.40mm viewing distance = .13592
Tan-1 (arctangent) of (.13592) = 7.74
7.74 x 2 = **15.48 degrees of visual angle** @ 533.40mm viewing distance

Experiment 1 visual angle calculation for participant-defined <u>'width'</u> of RED:
24.83mm width/2 = 12.415mm
12.415mm/533.40mm viewing distance = .02327
TAN-1 (arctangent) of (.02327) = 1.333
1.333 x 2 = **2.666 degrees of visual angle** @ 533.40mm viewing distance

Experiment 1 visual angle calculation for participant-defined <u>'width'</u> of ORANGE:
10.27mm width/2 = 5.135mm
5.135mm/533.40mm viewing distance = .00962
TAN-1 (arctangent) of (.00962) = .5116
.5116 x 2 = **1.102 degrees of visual angle** @ 533.40mm viewing distance

Experiment 1 visual angle calculation for participant-defined <u>'width'</u> of YELLOW:
13.83mm/2 = 6.915mm
6.915mm/533.40mm viewing distance = .01296
Tan-1 (arctangent) of (.01296) = .74251
.74251 x 2 = **1.485 degrees of visual angle** @ 533.40mm viewing distance

Experiment 1 visual angle calculation for participant-defined <u>'width'</u> of GREEN:
29.07mm/2 = 14.535mm
14.535mm/533.40mm viewing distance = .02724
TAN-1 (arctangent) of (.02724) = 1.56
1.56 x 2 = **3.12 degrees of visual angle** @ 533.40mm viewing distance

Experiment 1 visual angle calculation for participant-defined <u>'width'</u> of BLUE:
15.88mm/2 = 7.94mm
7.94mm/533.40mm viewing distance = .01488
TAN-1 (arctangent) of (.01488) = .85249
.85249 x 2 = **1.705 degrees of visual angle** @ 533.40mm viewing distance

Experiment 1 visual angle calculation for participant-defined <u>'width'</u> of INDIGO:
11.09mm/2 = 5.545mm
5.545mm/533.40mm viewing distance = .01039
TAN-1 (arctangent) of (.01039) = .59528
.59528 x 2 = **1.190 degrees of visual angle** @ 533.40mm viewing distance

Experiment 1 visual angle calculation for participant-defined <u>'width'</u> of VIOLET:
39.99mm/2 = 19.995mm
19.995mm/533.40mm viewing distance = .03748
TAN-1 (arctangent) of (.03748) = 2.146
2.146 x 2 = **4.292 degrees of visual angle** @ 533.40mm viewing distance

Experiment 2 visual angle calculation for participant-defined <u>'width'</u> of RED:
24.83mm width/2 = 12.415mm
12.415mm/533.40mm viewing distance = .02327
TAN-1 (arctangent) of (.02327) = 1.333
1.333 x 2 = **2.666 degrees of visual angle** @ 533.40mm viewing distance

Experiment 2 visual angle calculation for participant-defined <u>'width'</u> of ORANGE:
10.27mm width/2 = 5.135mm
5.135mm/533.40mm viewing distance = .00962
TAN-1 (arctangent) of (.00962) = .55116
.55116 x 2 = **1.1023 degrees of visual angle** @ 533.40mm viewing distance

Experiment 2 visual angle calculation for participant-defined <u>'width'</u> of YELLOW:
13.83mm/2 = 6.915mm
6.915mm/533.40mm viewing distance = .01296
Tan-1 (arctangent) of (.01296) = .74251
.74251 x 2 = **1.485 degrees of visual angle** @ 533.40mm viewing distance

Experiment 2 visual angle calculation for participant-defined <u>'width'</u> of GREEN:
29.07mm/2 = 14.535mm
14.535mm/533.40mm viewing distance = .02724
TAN-1 (arctangent) of (.02724) = 1.5603
1.5603 x 2 = **3.1207 degrees of visual angle** @ 533.40mm viewing distance

Experiment 2 visual angle calculation for participant-defined 'width' of BLUE:
15.88mm/2 = 7.94mm
7.94mm/533.40mm viewing distance = .01488
TAN-1 (arctangent) of (.01488) = .85249
.85249 x 2 = **1.704 degrees of visual angle** @ 533.40mm viewing distance

Experiment 2 visual angle calculation for participant-defined 'width' of INDIGO:
11.09mm/2 = 5.545mm
5.545mm/533.40mm viewing distance = .01039
TAN-1 (arctangent) of (.01039) = .59528
.59528 x 2 = **1.1905 degrees of visual angle** @ 533.40mm viewing distance

Experiment 2 visual angle calculation for participant-defined 'width' of VIOLET:
39.99mm/2 = 19.995mm
19.995mm/533.40mm viewing distance = .03748
TAN-1 (arctangent) of (.03748) = 2.146
2.146 x 2 = **4.292 degrees of visual angle** @ 533.40mm viewing distance

Experiment 3 visual angle calculation for participant-defined 'width' of RED:
23.23mm width/2 = 11.615mm
11.615mm/533.40mm viewing distance = .021775
TAN-1 (arctangent) of (.021775) = 1.247
1.247 x 2 = **2.494 degrees of visual angle** @ 533.40mm viewing distance

Experiment 3 visual angle calculation for participant-defined 'width' of ORANGE:
10.51mm width/2 = 5.255mm
5.255mm/533.40mm viewing distance = .00985
TAN-1 (arctangent) of (.00985) = .56434
.56434 x 2 = **1.1286 degrees of visual angle** @ 533.40mm viewing distance

Experiment 3 visual angle calculation for participant-defined 'width' of YELLOW:
15.526mm/2 = 7.763mm
7.763mm/533.40mm viewing distance = .01455
Tan-1 (arctangent) of (.01455) = .83359
.83359 x 2 = **1.667 degrees of visual angle** @ 533.40mm viewing distance

Experiment 3 visual angle calculation for participant-defined 'width' of GREEN:
28.209mm/2 = 14.104mm
14.104mm/533.40mm viewing distance = .02644
TAN-1 (arctangent) of (.02644) = 1.5145
1.5145 x 2 = **3.029 degrees of visual angle** @ 533.40mm viewing distance

Experiment 3 visual angle calculation for participant-defined <u>'width'</u> of BLUE:
16.458mm/2 = 8.229mm
8.229mm/533.40mm viewing distance = .01542
TAN-1 (arctangent) of (.01542) = .88343
.88343 x 2 = **1.766 degrees of visual angle** @ 533.40mm viewing distance

Experiment 3 visual angle calculation for participant-defined <u>'width'</u> of INDIGO:
12.256mm/2 = 6.128mm
6.128mm/533.40mm viewing distance = .01148
TAN-1 (arctangent) of (.01148) = .65772
.65772 x 2 = **1.315 degrees of visual angle** @ 533.40mm viewing distance

Experiment 3 visual angle calculation for participant-defined <u>'width'</u> of VIOLET:
38.801mm/2 = 19.4mm
19.4mm/533.40mm viewing distance = .03637
TAN-1 (arctangent) of (.03637) = 2.082
2.082 x 2 = **4.1658 degrees of visual angle** @ 533.40mm viewing distance

APPENDIX B

INSTRUCTIONS

For this experiment, you're going to be using the joystick mounted on the crate below the table. Just place one leg on each side of the crate and move your chair forward so that you can grab the joystick in your left hand. The crate and joystick are located under the table so that you cannot have any eye contact with your hand during the experiment.

Now, place your right hand on the mouse while your left hand is on the joystick located under the table on the crate positioned between your legs. This is the position you will be in while you are doing the experimental trials. The joystick will move in your hand in some way, shape, or form, and then you will make a choice on the screen by clicking on something with the mouse—you will do this 50 times. You will understand what choices will be available to you on the screen after you have read the directions to the experiment.

Simultaneously, while doing the experiment, you will have the headphones on and you will be hearing 'white noise' in your ears. White noise sounds just like TV or radio static when the TV or radio is not tuned to any station. The white noise assures that everyone has the same hearing experience during the trials, and prevents any distractions or noise that might be present in the hallway outside.

To begin the experiment just put on the headphones and fill out the information on this screen (pointing demographics information screen) by typing in your information answering the questions to the best of your ability. After you have filled out the information, just click the 'submit' button and you will be presented with the instructions that will explain in detail what you are to do. If you need any help just click the 'help' button on the screen at anytime to re-read the instructions.

APPENDIX C

GLOSSARY OF TERMS

Albedo:
A ratio of scattered to incident electromagnetic radiation power, most commonly light; a unitless measure of a surface or body's reflectivity, the word is derived from albus, a Latin word for "white"

Cross-sensory/Cross-modal:
Perception relating to both synesthesia (synaesthesia) and sensory substitution. Crossmodal perception, crossmodal integration and crossmodal plasticity of the human brain are increasingly studied in neuroscience to gain a better understanding of the large-scale and long-term properties of the brain. A related research theme is the study of multisensory perception and multisensory integration

CPD (cycles per degree):
Cycles per degree (CPD) measures how much an eye can differentiate one object from another in terms of degree angles

DDR:
Double-data-rate synchronous dynamic random access memory is a type of memory integrated circuit used in computers.

DPI:
Dots per inch (DPI) is a measure of printing resolution, in particular the number of individual dots of ink a printer or toner can produce within a linear one-inch space

Emergent property:
Emergence is the process of complex pattern formation from more basic constituent parts or behaviors, which manifests itself as an emergent property of the relationships between those elements.

Event related potentials (ERP’s):
Any stereotyped electrophysiological response to an internal or external stimulus; any measured brain response that is directly the result of a thought or perception.

Force-feedback:
Vibrational physical feedback provided to the hand or other part of the body via some type of control/response device such as a joystick, helmet, or seating apparatus

Frequency:
The number of complete oscillations per second of energy (as sound or electromagnetic radiation) in the form of waves

Gaussian:
Of or relating to Karl Gauss or his mathematical theories of magnetics or electricity or astronomy or probability; "Gaussian distribution"

GHz (gigahertz):
1,000,000,000 Hz

Grating:
Any regularly spaced collection of essentially identical, parallel, elongated elements. Gratings usually consist of a single set of elongated elements, but can consist of two sets, in which case the second set is usually perpendicular to the first

Hertz:
A unit of frequency equal to one cycle per second -- abbreviation Hz

Kilohertz:
1000 Hz

MB:
A megabyte is a unit of information or computer storage equal to approximately one million bytes. It is commonly abbreviated MB

PCI:
Peripheral Component Interconnect, or PCI Standard (in practice almost always shortened to PCI) specifies a computer bus for attaching peripheral devices to a computer motherboard

Piezo-electric:
Of, relating to, marked by, or functioning by means of piezoelectricity; electricity or electric polarity due to pressure especially in a crystalline substance (as quartz)

Proprioceptive:
Of, relating to, or being stimuli arising within the organism; a proprioceptive sensation; proprioceptive feedback

QWERTY:
The most common modern-day keyboard layout on English language computer and typewriter keyboards; It takes its name from the first six letters seen in the keyboard's top first row of letters
RAM:
Random-access memory (usually known by its acronym, RAM) is a type of data store used in computers that allows the stored data to be accessed in any order — that is, at random, not just in sequence

Resonance:
A vibration of large amplitude in a mechanical or electrical system caused by a relatively small periodic stimulus of the same or nearly the same period as the natural vibration period of the system

ROYGBIV:
A popular mnemonic device used for memorizing the traditional optical spectrum of red, orange, yellow, green, blue, indigo, violet

Sinusoidal wave:
A waveform that represents periodic oscillations in which the amplitude of displacement at each point is proportional to the sine of the phase angle of the displacement and that is visualized as a sine curve

Spatial frequency:
A characteristic of any structure that is periodic across position in space. The spatial frequency is a measure of how often the structure repeats per unit of distance.

Square wave:
A basic kind of non-sinusoidal waveform encountered in electronics and signal processing. An ideal square wave alternates regularly and instantaneously between two levels, which may or may not include zero.

Synesthesia:
A subjective sensation or image of a sense (as of color) other than the one (as of sound) being stimulated; the condition marked by the experience of such sensations

Tactile:
Of, relating to, or being the sense of touch

Tactual:
Latin *tactus* sense of touch

Triangle wave:
A basic kind of non-sinusoidal waveform named for its triangular shape. Like a square wave, the triangle wave contains only odd harmonics.

Twip:
A twip or TWIP (loosely from twentieth of a point) is a typographical measurement, defined as 1/20 of a typographical point. One twip is 1/1440 inch or 17.639 µm when derived from the PostScript point at 72 to the inch, and 1/1445.4 inch or 17.573 µm based on the printer's point at 72.27 to the inch

Vibrational periodicity:
The period of time it takes one cycle of a vibration to complete

Visual angle:
The angle that a visual stimulus subtends at the eye or the angle between the light rays from the two ends of the viewed object as they hit the eye; usually measured in degrees or minutes of arc.

White noise:
A heterogeneous mixture of sound waves extending over a wide frequency range