ARTICLE
An Undergraduate Laboratory Exercise to Study Weber's Law

Jameson K. Holden, Eric M. Francisco, Zheng Zhang, Cristina Baric & Mark Tommerdahl
Biomedical Engineering Department, University of North Carolina, Chapel Hill, NC 27599.

Weber's Law describes the relationship between actual and perceived differences in stimulus intensity. To observe the relationship described in this law, we developed an exercise for undergraduate students, as experiential learning is an integral part of scientific education.

We describe the experimental methods used for determining the subject's discriminative capacity at multiple vibrotactile amplitudes. A novel four-point stimulator (designed and fabricated at the University of North Carolina) was used for the study. Features of the device, such as automated skin detection, make it feasible to perform this laboratory exercise in a reasonable lab period.

At the conclusion of the lab exercise, students will thoroughly understand the principle of Weber's Law as well as fundamental quantitative sensory testing concepts. This introduction to sensory testing will provide a suitable foundation for the undergraduate neuroscience student to investigate other aspects of sensory information processing in subsequent lab exercises.

Keywords: Weber's Law; vibrotactile amplitude discrimination; just noticeable difference

The perceived intensity of a sensory stimulus relative to other stimuli is often difficult to quantify; a subject cannot easily tell whether one stimulus felt twice, half, or three quarters as strong as another. Nevertheless, it is easy to determine which of two stimuli is stronger, provided that the difference between the stimulus intensities is sufficiently large. The minimum physical difference that the subject can perceive -- the just noticeable difference (JND) or difference limen (DL) -- can be measured (Geschieder, 1991).

Ernst Heinrich Weber took advantage of the quantifiable nature of the DL in his 1834 study of perceived intensity. In his experiments he found the DL of blindfolded subjects by giving them two weights of equal magnitudes (standard weight) to hold in each hand. He then proceeded to add slightly heavier weights (test weight) to one hand. The subject was asked to compare the weights in both hands and determine which was larger. Weber found that it was more difficult for the subject to determine that there was a difference in the weights when the standard weight was larger; the size of the DL was proportional to the stimulus strength and increased linearly as the initial weight increased (Goldstein, 2002).

Based on Weber's experiments, physicist Gustav Theodor Fechner developed Weber's law: $\frac{\Delta S}{S} = K$, where *ΔS* is the difference limen (DL) corresponding to the reference stimulus *S*, and *K* is a constant called Weber's Fraction. By publishing this finding in 1860 in the text *Elemente der Psychophysik,* Fechner became the father of the branch of psychology coined 'psychophysics.' Research has shown that Weber's Fraction is constant for a range of stimulus intensities and can be applied to most senses, including touch, sight, and hearing (Formankiewicz and Mollon, 2009; Pienkowski and Hagerman, 2009).

This laboratory exercise was designed for undergraduate students to study Weber's law and its applications to sensory tactile stimulation through the determination of DLs at varying stimulus strengths (Francisco et al., 2008). Each test will consist of delivering a standard and a test sinusoidal vibrotactile stimulus simultaneously to the index and middle fingers of the right hand, after which the subject will choose which stimulus felt more intense. A series of these trials will be carried out, with the objective of determining the subject's difference limen. Students will use the Cortical Metrics Stimulator (CM-4; Cortical Metrics, LLC; Tannan et al., 2007) for these tests. It is an ideal tool for such an experiment as it can deliver up to four vibrotactile stimuli simultaneously, eliminating the need for memory in comparing sequentially delivered stimuli. It also has features such as automatic skin detection that add to the ease and speed with which the lab may be carried out.

LEARNING OBJECTIVES

1. After completion of the experiment, students should have a fundamental understanding of Weber's Law and its applications to tactile stimuli.
2. They should be able to describe the relationship between the physical intensity of a stimulus and perceived intensity.
3. They should understand the advantages of using larger sample sizes as opposed to smaller ones.
4. They should be familiar with the operation procedures of the Cortical Metrics Stimulator as well as fundamentals of sensory data collection and analysis.

MATERIALS AND METHODS

Materials

The Cortical Metrics CM-4 four-point vibrotactile stimulator (Figure 1) was used to conduct the exercise. It interfaced with a personal computer (laptop) through an internal data acquisition box (DAQ) made by National Instruments (NI DAQ USB-6259). The DAQ connects to the computer through a USB cable. The interface software was developed using Microsoft's .NET Framework v3.5. All computers were networked together to allow centralized data storage in the Cortical Metrics Neurosensory Diagnostics Database. This allowed for instant on-line data analysis at the end of the exercise.

Figure 1. Cortical Metrics (CM-4) Stimulator. INSET: Subject's hand properly positioned on the stimulator.

Procedures

One of the subject's hands was placed on the ergonomic armrest, while the other hand was used to press one of two buttons, located on a response device (mouse) connected directly to the PC.

One trial consisted of the delivery of two simultaneous vibrotactile stimuli, each through independent probe tips, for the duration of one half of a second. These stimuli consisted of 25 Hz sinusoidal vibrations of the probe tips at protocol-specified amplitudes. One of the two stimuli, the standard, was delivered at a constant amplitude throughout a run. The other stimulus, the test, was delivered at amplitudes that were always greater than the amplitude of the standard, but were otherwise varied according to the tracking method used. The digit locations of both the test and standard stimuli were assigned randomly by the computer. The subject responded as to which stimulus felt more intense by clicking the left or right button on the response device, assigned respectively to the left or right digit.

A modified Békésy method, also known as the staircase or up and down method, was used to track subject performance (Cornsweet, 1962). The Békésy method is an adaptive tracking method in which each test stimulus amplitude depends on both the preceding test stimulus amplitude and the subject's response. In this particular experiment, two variations on the Békésy method were used. At the beginning of a run, tracking was conducted with a bias of one: a correct identification of the greater amplitude stimulus lead to a decrease in the test amplitude by a specified step size and an incorrect answer lead to an increase in test amplitude by the same step size. Later in the run (after 10 trials) a bias of two was added to the tracking method; a subject had to deliver two consecutive correct answers for the test amplitude to decrease by one step size, while one incorrect answer lead to an increase in test amplitude by one step size. The bias of one for the first ten trials allowed for the subject to track down quickly, while later increasing the bias to two, increases the accuracy of the results of the run by decreasing the effects of good guessing (Tannan et al, 2006). The method stopped after 20 completed trials. During a run a subject was able to track down to the smallest test amplitude which he/she could consistently differentiate from the standard, that subject's discrimination threshold (JND).

For each run, the test amplitude started at twice the standard amplitude. The step size at which the test amplitude was increased or decreased was 10% of the standard stimulus (e.g., 0.02 mm for a 0.20 mm standard). These settings allowed the test stimulus strength to start out well above the discrimination threshold, but low enough for the subject to track down to his/her JND within the twenty trials that were administered during the run: experience has shown that most subjects can reach their discrimination threshold within ten to fifteen trials.

The standard amplitudes for each run were as follows: 0.2, 0.4, 0.6, 0.8 mm. Maximum and minimum amplitudes were user specified in the protocol so that the stimulator only delivered amplitudes within its proper operating range (0-2mm). The maximum amplitude was set to 3X the standard, while the minimum amplitude was set to the standard amplitude plus 5um. For example, for the first test (0.2 mm standard and 0.40 mm test) the minimum amplitude was 0.205 mm.

After each run was completed, the program generated a graph of the test amplitude versus trial number (Figure 2). It also displayed the discrimination threshold. From previous experience it was determined that most subjects reach their discrimination threshold by the last five trials of a test; therefore the average of the last five test amplitudes is used as the discrimination threshold. The subject's discrimination threshold was determined for each test, and data was subsequently collected from all students in the class (n=11).

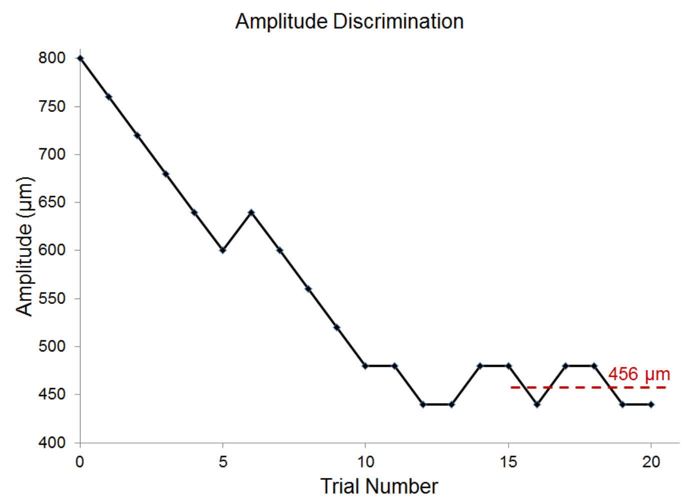

Figure 2. Example program output after completion of a single test run (Standard = 400 µm).

The difference limen (DL) for each subject was determined by subtracting the standard amplitude from its corresponding final test amplitude for each run. The averages of the DL at each standard amplitude were determined for a sub-group of five students as well as for the entire class. These averages were useful in teaching about the effects of sample size. The students then compared their own DL (n=1) with the average DLs for the group of selected sub-group five people (n=5), as well as the entire class (n=11). Separate plots of DL versus standard amplitude were then constructed for each group. Students compared the three different graphs in order to evaluate the effects of increasing the sample size on experimental results. Students also considered the general form of these graphs and verified that it was in accordance with the linear relationship predicted by Weber's law.

RESULTS AND DISCUSSION

A sample plot for the group of 11 students is shown below (Figure 3). The data we collected from this group of 11 students supported the linear relationship between the difference limen (*ΔS)* and the standard amplitude (*S)* predicted by Weber's Law, and plotting this data resulted in a nearly linear graph, with a linear correlation coefficient of 0.994. The data from the group of five students along with the data from a single individual were still roughly linear, but much less so, with linear correlation coefficients of 0.935 and 0.794, respectively. Clearly, larger sample sizes gave a better approximation of Weber's Law than smaller sample sizes.

Discussion

The exercise was designed to introduce students to Weber's Law using the CM-4 Stimulator as a tool in quantitative testing and measuring of sensory perception. Weber's Law was selected as the subject of this lab because it provides an easily understandable concept as well as a simple protocol for students to test. The CM-4 stimulator was the instrument of choice due to its particular suitability to the task at hand, as well as its versatility, making it a particular valuable research tool to understand. The CM-4 stimulator has a wide range of applications in the area of tactile sensory testing. Simple protocols and portability not only make it ideal for an undergraduate lab setting but for clinical testing and research as well. The integrated software makes it possible to execute protocols that can be adjusted and applied without constant human intervention. The automatic skin detection and programmable test parameters that enable precise control of the amplitude and frequency of stimuli allow for reproducible protocols and reduction of sources of error.

By the end of the exercise paper, students gained a conceptual understanding of Weber's law and its application to sensory testing. Students saw the value of larger experimental sample sizes as well as becoming familiar with the fundamentals of tactile sensory data collection and analysis. The linearity of the collected data is easy to understand, and since linearity in any biological study is rare, we view this result as significant and robust, especially given that it can be collected in a classroom/laboratory setting.

To verify that students accomplished the learning objectives laid out in the introduction of this paper, the instructor may elect to distribute a short quiz. The assessment should be short, and could consist of short-answer questions/problems such as the four below:

1. Define Weber's Law.
2. Provide an example of how Weber's Law relates to tactile perception.
3. Design an experiment to test Weber's Law.
4. When empirically evaluating a scientific hypothesis, is a large or small sample size preferred? Why?

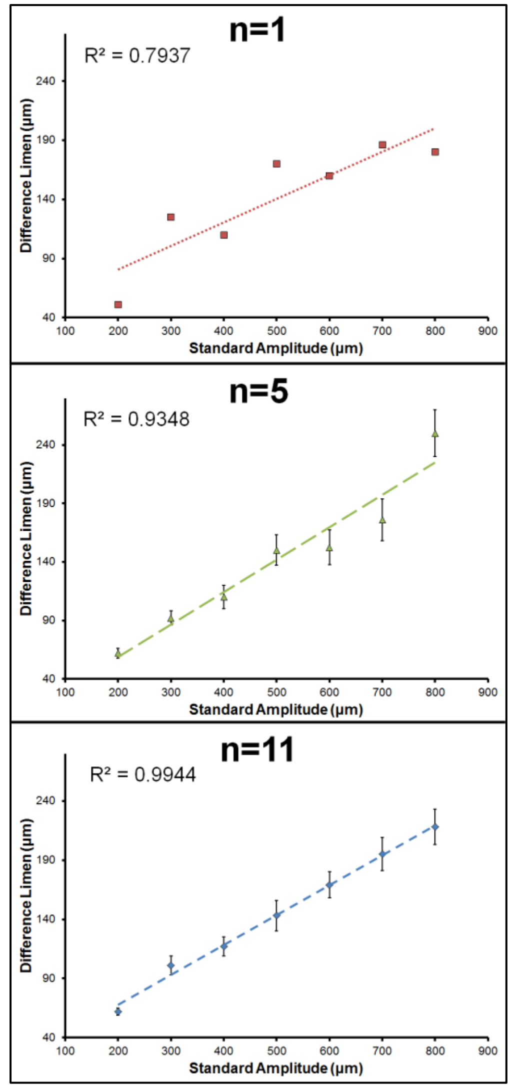

Figure 3. Graph of Difference Limen vs. Standard Amplitude for each sample set (n=1,5, and 11). Error bars at each point represent the standard error.

REFERENCES

Cornsweet TN (1962) The staircase-method in psychophysics. Am J Psychol 75:485-491.

Fechner GT, Elemente der Psychophysik. 1860.

Francisco EM, Tannan V, Zhang Z, Holden JK, Tommerdahl M (2008) Vibrotactile amplitude discrimination capacity parallels magnitude changes in somatosensory cortex and follows Weber's Law. Exp Brain Res:49-56. Epub 2008 Jul 24.

Formankiewicz MA, Mollon JD (2009) The psychophysics of detecting binocular discrepancies of luminance. Vision Res 49:1929-1938. Epub 2009 May 19.

Gescheider GA (1991) Psychophysics: The fundamentals. Mahwah, NJ: Lawrence Erlbaum Associates.

Goldstein, EB (2002) Sensation and Perception. Belmont, CA: Wadsworth Group.

Pienkowski M, Hagerman B (2009) Auditory intensity discrimination as a function of level-rove and tone duration in normal-hearing and impaired subjects: the "mid-level hump" revisited. Hear Research. 253:107-15. Epub 2009 Apr 2.

Tannan V, Whitsel B, and Tommerdahl M (2006) Vibrotactile adaptation enhances spatial localization. Brain Res 1102:109-116

Tannan V, Dennis RG, Zhang Z, and Tommerdahl M (2007) A portable tactile sensory diagnostic device. J Neurosci Methods 164:131-138.

Received October 06, 2010; revised December 07, 2010; accepted November 23, 2011.

This work was supported, in part by the Department of Defense, Congressionally Directed Medical Research Program (CDMRP W81XWH-07-1-0287) and NIH 5R90DA023417-03.

Address correspondence to: Dr. Mark Tommerdahl, Department of Biomedical Engineering, University of North Carolina, Chapel Hill, NC 27599. Email: mark_tommerdahl@med.unc.edu