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Functional homologies between human perceptual systems – In what ways do the senses employ similar processing principles?

Introduction

In this essay I will survey several key similarities between the human perceptual systems, demonstrate how they affect our abilities to perceive the world and attempt to explain the rationale for their existence.

Contrast based perception

Probably the most notable similarity common to the human perceptual systems is the notion of contrast. While the physical properties of precepts (whether it is light intensity, sound amplitude, pressure on skin or number of odorant molecules reaching our nose) may vary by up to a million time and more in intensity, it seems that the local contrasts of stimuli, both in space as well as in time, is what our perceptual systems are mainly tuned to follow. In the visual system, we note how simultaneous contrast effect gives us illusions of different brightness as being equal, and how the illuminant of the background is discounted from the colors and brightness of objects in the image[1]. This property of vision can be traced to the ganglion cells in the retina, which perform differentiation of the receptive field, and the habituated nature of the visual system's neurons that stop responding when the image they perceive remains fixed for a long duration. Similarly, the audio system perceives melody with disregard to the absolute values of the frequencies of different notes, as long as their relative pattern remains identical[2].

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1 Lotto (2002)
[2] Dorrell (2005)

Adaptation of the tactile, olfaction and taste systems to consistent temperature odors and tastes (respectively) has also been shown to occur[3], allowing us to discern differences in stimuli if and when they are significant enough[4].

The perception of contrast plays a vital evolutionary role, allowing negation of irrelevant constant information in favor of sudden changes across time and local differences in stimuli across space. Stagnant objects are rarely of interest to a living being (rocks, a large desert etc.), things that move (such as threats) and things that show difference in contrast (fruit in the middle of a bush, predator hiding in the woods) could prove vital to survival.

Non-linear scale

The non-linear scale of perception is tightly related to the contrast based perception. It is one of the basic properties that allow the human perceptual systems its enormous range of perception. The non-linear nature of human perception systems has been elegantly captured by Weber's law, which states that the relation between the physical energy of various stimuli and their perceived intensities is on the scale of the natural logarithm, and later by Steven's power law which refined the logarithm base for different senses and different types of stimuli for each sense. The logarithmic scale is clearly evident in music perception, as doubling the frequency of the sound is characterized perceptually as raising it an octave, leaving the tone "chroma" (perceptual "character") unchanged. In the visual system, the perception is nearly linear (low logarithmic base), but a difference is still noticeable (see figure 1).

Figure 1 – Linear intensity bands, perception not linear – usually 2nd and 3rd from the left appear much more different then the 2nd and 3rd from the right (note - different displays may affect intensities)

[3] Reviewed by Frisancho (1993); studied, for example, by Zufall (2000)
[4] Stevens (1957)

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Categorical Perception

While our senses perceive immense amounts of nearly continuous information from the environment, our perception remains to the most part categorical. This is easily noticeable in speech, where different combinations of acoustic frequencies are categorized into a discrete set of syllables with no intermediate non-categorized values, nor distinction between extremely different frequency combinations from the same category[5]. A visual form of this concept can be found in images morphing between two categorical precepts[6], and in color separation, where two colors with a constant difference in wavelength will be perceived as more similar if they fall into the same category[7]. An extreme case is illusions such as the Rabbit-Duck[8], showing that even the exact same stimuli can be classified into different categories at different occasions. While little work has been done on categorical perception in other senses (touch, smell, taste) many researchers agree they also show forms of categorical perception, and some show preliminary results in this direction[9].

Categorical Perception could also be attributed to the practical nature of the senses. It is safe to assume that the main utilization of the senses has evolutionarily been to perform separations: edible from poisonous, potential mate from predator, etc. This makes categorical perception an important aspect of all human perceptual systems. It is also interesting to note that the neural network model used and studied by engineers and computer scientists, although not entirely similar to our understanding of the biological neurons in the human brain, has been shown to be most useful in classification and pattern matching tasks[10], both of which demonstrate categorical character.

5 Liberman, Harris, Hoffman and Griffith (1957)
6 Campbell, Pascalis, Coleman, Wallace, Benson (1997)
7 Berlin & Kay (1969)
8 Attributed to Jastrow (1900)
9 Examples for such references: Harnad (1987), Riesenhuber & Poggio (1999), Zelano & Sobel (2005)
10 Lippmann (1989)

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Summary

The perceptual systems exhibit many similarities. Some notable ones neglected in the discussion of this essay include direct topography with differential resolution (retinotopic visual cortex with concentration in the fovea, tonotopic audio cortex with concentration on middle frequencies, somatotopic homunculus with a larger concentration of nerves from specific regions, etc.), adaptation and opponent processes (fixation blindness, waterfall effect, frequency negation), coupled senses (two eyes, ears and nostrils all used to detect sources of stimuli) and "Filling in" (blind spot, illusory contours, basic frequency). These similarities are to be expected, as a common evolutionary thread binds them together. Apart for their shared functional characteristic the fact that all senses have a similar neuronal pathway via the thalamus (except for smell) as well as a similar neuronal structure at the end of the pathway provides them all with a similar computational basis. This can probably be attributed to their mutual evolution, and it is only natural that during this period they have been prone to sharing qualities, especially those correspondences that preserved an evolutionary advantage. In fact, it is the dissimilarities between perceptual systems that are unexpected, and the motives for emerging diversity in them that invites interest and further investigation.