THE EVOLUTION OF PSYCHOPHYSICS: FROM SENSATION TO COGNITION AND BACK AGAIN

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Abstract

For over a century, psychophysicists have attempted to understand the processes by which physical properties of stimuli are mapped into mental representations. Early investigations followed a model in which physical energy was transduced into neural impulses, with the information in these impulses being conveyed to the central nervous system where they gave rise to sensations (a bottom-up information-processing model). Even when it was recognized that there were interactions among stimuli (e.g., center-surround contrast in vision), these interactions were assumed to occur early in the information-processing stream (e.g., on-center and off-surround receptive fields). Hence, the implicit bias towards a bottom-up process remained. Within the last 40-50 years, however, it has become apparent that top-down factors (e.g., expectations) and a person's cognitive abilities (e.g. working memory capacity) also affect how information is gathered and processed. These recent developments have forced us to refine our models to include sensory-cognitive interactions.

Psychophysics began as an attempt to link the physical dimensions of stimuli to their mental representations. Hence, for over a century, psychophysicists have attempted to understand the processes by which, say, the intensity of a pure tone, or the luminance of a circular patch of light, was mapped into sensations of loudness and brightness, respectively.

Early investigations followed a model in which physical energy was transduced into neural impulses, with the information in these impulses being conveyed by neural pathways to the central nervous system where they gave rise to sensations. In other words, the mapping of physical intensity into mental events was implicitly assumed to be a bottom-up process. Later work showed that the sensation associated with, for instance, a circular patch of light, was affected by the surrounding conditions, and the Gestalt psychologists pointed out that the stimulus configuration mattered. Hence, it was soon recognized that there were interactions among stimuli that needed to be considered if we were to understand and model the manner in which physical stimuli were translated into mental representations. In keeping with the implicit bias towards a bottom-up process, these interactions were often assumed to occur early in the information-processing stream. For example, interactions among photoreceptors produced center-surround antagonism in retinal ganglion cells, thereby providing a sensory basis for contrast effects. Hence, models of information processing remained largely bottom-up. However, within the last 40-50 years it has become apparent that the observer's knowledge and/or expectations can alter the mental representation of stimuli. In other words top-down factors (e.g., attentional focus, expectations, knowledge) affect how information is gathered, processed, and stored. Moreover, when perceptual psychologists began to investigate how complex stimuli are processed (e.g., words in sentences, faces in complex scenes), it became clear that cognitive factors (e.g. working memory capacity, executive control) were also involved in how physical stimuli gave rise to mental representations. This paper will examine how these trends have forced us to reconsider and refine our models of how physical stimuli are translated into mental representations. Fortunately, the tools that psychophysics has developed are eminently suited for this kind of investigation.

The effects of context on loudness judgments

In a seminal paper Marks (1988) reported that equal loudness matches inferred from magnitude estimates of loudness for tones of two different frequencies intermixed in the same session were affected by changes in the ranges of intensities employed at each frequency. In other words, the magnitude estimate assigned to a 65-dB (SPL), 500-Hz tone might equal that assigned to a 70-dB (SPL), 2500-Hz tone when the 500-Hz tones ranged from 35 to 75 dB, and the 2500-Hz tones ranged from 50 to 85 dB, but equal that assigned to a 53-dB 2500-Hz tone when the 500-Hz tones ranged from 55 to 90 dB, and the 2500-Hz tones ranged from 30 to 65 dB. Hence, loudness matches obtained from magnitude estimates were strongly affected by stimulus context. Schneider and Parker (1990) and Parker and Schneider (1994) showed that these effects were not due to response bias but rather indicated that the sensory representation itself, was affected by the range of intensities encountered by a listener during a session. To account for these effects Parker and Schneider (1994) proposed that the sensory representation of a sound's intensity was under the control of a nonlinear amplifier which modified the growth of loudness with intensity (e.g., changed the exponent of the loudness function), where the extent of the modification depended on the highest intensity experienced by the listener. They also hypothesized that the function of the amplifier was to protect against sensory overload while maximizing discriminability among the stimuli within a certain range.

More recently, Parker, Murphy, and Schneider (2002) and de la Rosa, Gordon, and Schneider (2009) showed that the extent of modification of the function relating intensity to sensation depended on the perceiver's expectations as to the intensity of the stimulus to be presented. For example, de la Rosa et al. had participants identify visually presented sine-wave gratings, varying in contrast, in an absolute identification (AI) paradigm. Each presentation of a grating was preceded by one of two possible fixation stimuli. In the baseline condition, which consisted of four low-contrast gratings, the cues were randomly paired with the different gratings, that is, the cues did not predict the contrast of the grating to be presented. In a second condition, a fifth high-contrast grating was added to the set of four baseline gratings, but again, the cues were randomly paired with the different gratings. de la Rosa et al. found that the inclusion of an unpredictable high-contrast grating among the set of four low-contrast gratings dramatically reduced the observer's identification accuracy for the four low-contrast stimuli. But, when the same five stimuli were presented in a third condition in which the high-contrast stimulus was always preceded by one of the cues, and low-contrast stimuli were always preceded by the other cue, so that the observer always knew when the high-contrast grating would occur, the inclusion of a high-contrast stimulus in the set had no effect on identification accuracy for the four low-contrast gratings. Hence, the function controlling the mapping of intensity to sensation depends on the predictability of the stimuli. When participants expect that a high-intensity stimulus will occur, but are unable to predict precisely when, they set the gain to low to protect against the occasional occurrence of a high-intensity stimulus. However, when they are able to predict its occurrence they appear to be able to lower the gain just before it occurs, and then increase the gain when a low-contrast stimulus is expected. Hence, the gain of the amplifier appears to be under top-down control. Moreover, when the cues are informative Mišić, Schneider, and McIntosh (2010) found two robust spatiotemporal patterns of electrical brain activity associated with preparation for upcoming targets whose contrast was predicted by a cue. Moreover, the patterns differed depending upon whether the cue signaled the imminent occurrence of a high- or low-contrast gratings. Hence these two patterns provide electrophysiological indicators of knowledge-driven preparation for a large change in sensory intensity.

Top-down, knowledge-driven effects in identification and recognition of complex stimuli

Given that the encoding of the basic properties of a stimulus is under top-down, knowledge-driven control, there is every reason to believe that the representations of auditory and visual objects will be affected by individuals' knowledge and expectations concerning their current situation. For example, there is evidence that prior knowledge of the first five words of an anomalous spoken sentence such as "***A rose could paint a*** *fish*" can make it much easier to identify the final word "fish" when the complete sentence is simultaneously masked by either a steady-state speech-spectrum noise, or by two different anomalous sentences spoken by two other people. (Note that in this case prior knowledge of the first five words does not reduce the number of possible nouns that could appear as the sixth word). For example, Ezzatian, Li, Pichora-Fuller & Schneider (in press) determined the signal-to-masker ratio necessary for 50% correct identification of the final word of anomalous sentences when the masker consisted of anomalous sentences spoken by two competing talkers under two conditions. In the first condition, the target sentence started 1 s after the competing talkers and the listener was asked to repeat the whole target sentence. In the second condition, the listener heard all but the last word of the target sentence before the same sentence was presented in the presence of competing speech, and found that the signal-to-masker ratio needed for 50% correct identification was 2-4 dB higher in the first condition than in the second. Hence, prior partial knowledge of the context within which the target is embedded (e.g., the first five words of the sentence "A rose could paint a fish") will enhance the likelihood that the target word will be correctly identified even when the context does not alter the predictability of the target word.

Moreover, that this effect is due to top-down influence is indicated by the fact that the partial sentence does not even have to be presented in the same modality, since Freyman, Balakrishnan, and Helfer (2004) have shown the effect is the same when all but the last word of the anomalous sentence is presented on a monitor rather than being heard.

At what level is knowledge influencing detection, discrimination, and recognition?

We have seen that the observer's expectations as to the intensities of stimuli that might be presented, nonlinearly alters their transduction into sensory magnitudes. Hence it is reasonable to ask: At what level of the information-processing stream is knowledge exerting its effect? It is here that psychophysical methods can be most helpful. For instance, in audition, it is possible that knowledge alters the transduction of acoustic energy into nervous impulses by modulating the action of the outer hair cells by means of the efferent fibers from the olivo-cochlear bundle. Because these hair cells control the amount of amplification in the cochlea, efferent control over them could be part of the gain-control mechanism. If one of the functions of the gain-control system is to protect against overload, it would make sense to dampen the gain on the cochlear amplifier based on the listener's experience or expectations concerning the intensity of stimulation to that ear. If that were true then we would not necessarily expect that occasionally presenting a loud sound to the left ear would affect the discriminability of sounds presented to the right ear. Indeed, Gordon and Schneider (2007) found that identification of the four low-intensity tones in a set of five tones (25, 30, 35, 40, and 80 dB SPL) was significantly better when the four low-intensity tones were presented to one ear and the high intensity tone to the other, than when all five tones were presented to the same ear. This result is consistent with the hypothesis that knowledge of the tonal intensities that could be presented to an ear modifies the action of the cochlear amplifier in that ear.

A similar application of psychophysical techniques could help to determine how, for instance, prior partial knowledge makes it easier to identify target words when they are masked by noise or competing speech. Hearing the first five words could aid in segregating the target voice from the background noise (Bregman, 1990) by giving the listener an auditory template to match, which suggests that unmasking occurs at a relatively early level in the information processing stream. Or, instead of using grammatically correct but semantically anomalous sentences, one could use a string of unrelated words. If that change diminished the degree of unmasking, it would suggest that syntactic structure was crucial to the phenomenon, and that, therefore, higher-level processes are involved. Psychophysicists have the tools and background that would enable them, in collaboration with experts in other fields (e.g., linguistics) to enlarge our understanding of these processes.

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