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A. M. Sherman and M. O'Connor

Memory Psychophysics

Memory psychophysics, or mnemophysics, is the branch of psychophysics that treats the functional relations between physical stimuli and their remembered sensory responses or representations. The name implicates the parent disciplines of memory and psychophysics. Memory researchers have long explored the reliability of representing the past, pursuing the relationship between the objective properties of stimuli that are no longer present(ed) and their current, remembered representations. Classical psychophysics, however, deals with the relationship between the physical properties of the momentary stimuli impinging on the sensory surface and the instantaneous sensations or perceptual representations. With the affinity of the respective pursuits recognized, students of memory psychophysics have sought to deploy psychophysical theory and methods to elucidate the quantitative properties of memory-based judgments and representations. Memory psychophysics is a young field of inquiry, yet several emerging trends are already discernible. These developments are examined in chronological order. Considered first is their historical context, and the article concludes with remarks concerning the prospects of memory psychophysics.

1. Memory Psychophysics: Antecedents, Conjectures, and Modern Beginnings

The idea that memory is based on images, on seeing internal pictures, can be traced back to at least Aristotle, if not Plato (see Algom 1992a,b, for a historical perspective). Plato's notion of *eikon*, prevalent in his discussions of memory, refers to a copy or an image that holds considerable similarity to the original perception. In *De Memoria*, Aristotle suggests that people rely on small-scale internal models of the perceptual referent when they remember. Aristotle proposes a spatial-analog representation underlying the memory of scenes and events. The spatial images undergo continuous transformations that enable the person to date the original perception in time. Implying a shrinkage over time in the size of the memory image, Aristotle comes remarkably close to a reperception theory of memory, anticipating the current mnemophysical hypothesis bearing that name.

In the nineteenth century, several pioneers of psychophysics and psychology considered the idea of a psychophysics applied to memory. Fechner's little-read article from 1882 is titled, 'Some thoughts on the psychophysical representations of memories,' and Titchner's 1906 classic, *An Outline of Psychology*, explicitly acknowledge the discipline of memory psychophysics along with the strong assertion that memory obeys Weber's law. Wundt's psychology of consciousness similarly invites the perceptual study of memory, as does the work of Ebbinghaus on human memory, immensely influenced by Fechner's psychophysics.

Modern mnemophysics was (re)born in the Laboratory of Psychophysics at the University of Stockholm, Sweden. Bjorkman, Lundeberg, and Tarnblom (in 1960) were probably the first modern researchers to study, via rigorous psychophysical methods, the subjective magnitudes of perceptual (physically presented) and remembered (symbolically represented) stimuli in tandem. In the same laboratory, Dornic first applied Steven's power law of sensation to judgments of remembered stimuli. In a similar vein, Ekman and Bratfish and other researchers have asked people to assess inter- and intra-city distances, estimates that

International Encyclopedia for Social and the Behaviora Sciences. London: Elsevier must be considered to be forms of 'cognitive psychophysics' (cf. Wiest and Bell 1985, who should be consulted for a review) inasmuch as these stimuli can not be presented for view. Shepard and Chipman (1970) had people compare states of the continental USA on geometric similarity once perceptually (on the basis of outline shapes) and once from memory (on the basis of mere names). The respective sets of data were similar to the extent that Shepard and Chipman concluded that internal representations are second-order isomorphic to the referent physical stimuli. In another landmark study, Moyer (1973) had people select, while timed, the larger of two animals based on presentation of their names. Response time decreased as the difference in size between the referent animals increased ('symbolic distance effect'), mirroring the perceptual relation by which reaction time is inversely related to stimulus difference. Moyer invoked the notion of 'internal psychophysical judgment' to account for the data. Finally, Baird, another veteran of the Stockholm laboratory, explicitly proposed a cognitive theory of psychophysics in the early 1970s.

2. *Unidimensional Mnemophysics: Psychophysical Functions for Remembered Stimuli*

Ultimately, it was 1978 that ushered in the discipline of memory psychophysics. Two independent studies were published in prestigious journals, deriving psychophysical functions for remembered stimuli. In one, Moyer et al. (1978) had separate groups of people estimate the sizes of perceived and of remembered stimuli. Participants in the memory conditions were told to imagine each stimulus as its name (learned earlier) was called out, then assign a number in accord with standard magnitude estimation instructions. Separate psychophysical functions were then derived for the common set of physical stimuli, one for perceptual judgments, the other for judgments made from memory. The same method has been used in subsequent studies probing the gamut of sensory modalities from visual length, distance, area, volume, and brightness, to auditory loudness and volume, to dimensions of touch, taste, odor, and pain (see Algom 1992b, for a comprehensive review).

The following fundamental questions were pursued. How do remembered sensory magnitudes depend on referent physical magnitudes? Do memory scale values map onto their physical referents by means of the same functional relation (e.g., Steven's power transform) as do perceptual scale values? And if so, do the same parameters (exponents) govern perceptual and memory functions? Again, standard psychophysical methods and analyses can and have been used with both perceptual and memory types of judgment, the only procedural difference being that stimuli are in one case physically presented, in the other, symbolically represented.

Two general findings have emerged from these unidimensional studies of memory psychophysics. First, judgments from memory relate to the corresponding physical stimuli via power transforms in much the same way as perceptual judgments. Second, systematically smaller exponents govern the memory functions compared with the respective perceptual functions. For instance, in the aforementioned study by Moyer et al. (1978), perceptual area related to physical area by a power function with an exponent of 0.64, whereas remembered are related to physical area by a power function with an exponent of 0.46.

Two rival formulations have been suggested to account for properties of memory-based magnitude judgments. According to the reperception hypothesis, perception and memory perform identical (power) transformations on the input data. Because the input to memory processing has already been transformed perceptually (by exponent b), the memory exponent should reflect two transformations, and thus equal b^2. The alternative uncertainty hypothesis posits that greater uncertainty causes people to constrict the range of judgments or to expand the range of the underlying stimulus dimension, thereby producing an attenuated memory exponent.

The cumulative results provide qualified support for the reperception and the uncertainty hypotheses—in that order. Both theories predict smaller memory exponents for compressive perceptual continua (characterized by smaller-than-unity power function exponents), a prediction amply borne out by the extant data. However, clear resolution must await examination of expansive continua (characterized by greater-than-unity power function exponents) for which the reperception hypothesis predicts a steeper memory function, whereas the uncertainty hypothesis still predicts an attenuated memory function. Mnemophysical investigation of pain (Algom and Lubel 1994), an expansive sensory dimension, has provided qualified support for the reperception hypothesis.

The good fits to the memory functions obtained throughout the various studies affirm that, likely, more than just ordinal information is conserved. Nevertheless, the same studies are vulnerable on counts of validity, beset by indeterminacy of the functions relating sensations and memories to the corresponding overt responses. The issue cannot be solved within the confines of the univariate designs used.

3. *Multidimensional Mnemophysics: Rules of Stimulus Integration in Perception and in Memory*

Steven's contention that the psychophysical law is a power function depends on the strong assumption that the numbers given by participants (their overt responses) are proportional to sensation or memory magnitudes (their inner perceptions). However, Stevens provided no justification for this assumption. As a result, the validity of the power law and the associated findings and interpretations are suspect. The need for an adequate metric structure to support validity is as vital for memory psychophysics as indeed it is for the entire edifice of psychophysics (see Narens 1996, for a firm formal foundation for Stevens's approach).

Examination of multidimensional stimuli such as rectangles, mixtures of odor and of taste, or painful compounds, does provide the underlying metric structure needed for authenticating the overt response. The problem becomes tractable because the rules by which the components integrate—uncovered and tested by methods such as conjoint measurement or functional measurement—provide the necessary constraints to validate the psychophysical functions. Indeed, specification of the appropriate model of integration entails the scale—the psychophysical function—as its natural derivative. Most important in the context of memory psychophysics, deployment of multivariate methods enables the examination of a wholly novel class of questions. They concern the respective rules of integration in perception and memory pertaining to the same set of physical stimuli. Integration models have been specified for numerous stimuli using a perceptual response. Multivariate studies of memory psychophysics have established the complementary integration models for remembered stimuli. At issue is the constancy in form of stimulus integration in perception and memory.

For area of rectangles presented for view (Algom et al. 1985), the veridical height X width rule has been shown to underlie the perceptual judgments. The same multiplicative rule reappeared when the rectangles were not presented for view, but were represented instead by previously learned names ('remembered composites'). In another condition ('mental composites'), participants were trained to name a set of horizontal and vertical line stimuli varying in length. Subsequently, the participants were instructed to form imaginary rectangles whose sides were made of previously shown pairs of lines represented by a pair of appropriate names. Notably, the same height X width rule applied again, despite the fact that the stimuli were wholly imaginary (no physical rectangles had been presented). A third condition ('semimental composites') resembled 'mental composites' in that it entailed no presentation of the physical stimulus; judgments were based on the (separate) presentation of a physical line and a name (standing for another, perpendicular, line) to be considered by the participant as the respective sides of an imaginary rectangle. For semimental composites, too, the same height X width rule applied.

In displaying an invariance in the rules of multidimensional integration, visual area joins other continua, including additional visual attributes, smell, taste, and pain. For olfaction, to cite a single example, the same rule of synthesis has been shown to hold for physical, remembered, mental, and semimental mixtures of given odorants. The transrepresentational invariance also holds developmentally. When, in the course of development, perceptual integration changes (e.g., from addition to multiplication), so too does the corresponding memorial integration. The results may tap a general-purpose compositional strategy: integration rules are invariant across various processing stages of a given stimulus. The validated functions derived within the framework of multifactorial mnemophysics are commensurate with the earlier findings: memory functions are markedly more compressive than the respective perceptual functions (except for young children). Therefore, a given invariant rule of integration acts on different sets of scale values in perception and memory.

4. *Symbolic Comparisons*

A common mental activity of everyday life consists of comparing pairs of stimuli in their absence and deciding which contains more of the attribute of interest. Deciding which numeral in the pair, 8–2, is larger numerically, or deciding which name in the pair, cat–dog, refers to the larger animal, are common examples. Such comparisons entail symbols (typically, though not exclusively names or numbers) standing for the referent stimuli, and thus are necessarily based on information retrieved from memory. The symbolic distance effect, mentioned earlier, documents one characteristic of symbolic comparisons. The semantic congruity effect by which large pairs are compared faster under 'choose the larger stimulus' instructions and small pairs are compared faster under 'choose the smaller stimulus' instructions, documents another. A third phenomenon, the end effect, pertains to the fact that pairs of stimuli containing the smallest or the largest stimulus as a member are compared faster.

Note that the main dependent variable used in this research is response time (augmented, at times, by a measure of error), not magnitude estimation or other (nonspeeded) scaling estimates. This reflects a preoccupation with the substantive processes of learning, comparison, representation, and decision. Earlier developments in memory psychophysics, by contrast, mainly concerned scaling and organization. Indeed, research on symbolic comparisons and research on scaling and composition of single remembered stimuli has not been satisfactorily integrated to date. With the application to comparison data of advanced psychophysical techniques, this domain comes squarely under the purview of memory psychophysics.

A discrete, proposition-based, semantic coding account (Banks 1977) has been influential against rival 'analog' theories of the mental comparison process. More recently, evidence accrual decision models (e.g., Petrusic's 1992, Slow- and Fast-Guessing Theory), characterized at times as a 'random walk' (e.g., Link's 'Wave Discrimination Theory'), and connectionist networks (e.g., Leth-Steensen and Marley 2000), have been developed. A notable feature of these theories is their full alliance with mainstream psychophysics and cognitive psychology. By the same token, however, many recent models lack a treatment of the difference between comparisons made with physical and remembered stimuli. This difference, one should recall, is the *raison d'être* for the establishment of an independent discipline of memory psychophysics.

5. *Concluding Remarks*

The primary function of the senses is to guide ongoing behavior, yet they also exert considerable influences on memory associated with the original sensations. Sensations endure and inform cognition well beyond the physical presence of the triggering stimulus. It is those cognitions and memories that are captured and elucidated within memory psychophysics. As this article shows, there is a conceptual shift from scaling to cognizing in the pertinent research. This allows for the examination of a richer class of phenomena including decision, context, learning, and representation. The framework of single-variable scaling has been inhospitable to explicating process-based phenomena. Nevertheless, integrating scaling and comparison data remains a challenge to be met in future memory psychophysics.

See also: Learning Curve, The; Psychophysical Theory and Laws, History of; Psychophysics; Sensation and Perception: Direct Scaling; Visual Space, Geometry of

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D. Algom

Memory Retrieval

Memory retrieval is the recovery of stored information. It is a feature of virtually all cognitive activity, whether it be conducting an everyday conversation, planning a course of action, or making simple decisions. Yet, as with many cognitive processes, memory retrieval is a skill largely taken for granted. Only the experience of retrieval failure—a friend's name refusing to come to mind, or an interaction with someone suffering a severe memory disorder such as Alzheimer's disease—leads to an appreciation of memory's pervasiveness and to questions about the processes that underlie it. How does someone extract from the vast amount of stored information the one piece of information that the occasion demands? This article offers a brief account of what is currently known about these retrieval processes.

1. *Two Views of Memory Retrieval*

Two simple views provide a necessary foundation for the presentation of contemporary accounts of memory retrieval. One view claims that retrieval is determined by the state of the memory trace. The other claims that it depends on the presence of an effective retrieval cue.

1.1 *The Trace-dependent View of Retrieval*

The simplest account of memory retrieval assumes that it depends only on the strength of the memory trace relative to other traces. Retrieval failure occurs because the memory trace has become too weak, or because competing traces have become stronger than the target trace. Such a trace-dependent view of

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