Special Issue Commentary

The Role of Mathematical Psychology in Experimental Psychology

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In the history of cognitive psychology, there has always been a split between researchers with a theoretical, quantitative approach and researchers with an empirical, hypothesis-testing approach. Both approaches allow research to advance, but theory is the only way to see deeper relationships within experimental data. In this note, I first illustrate the split with the example of implicit memory research, and then I focus on what quantitative theoretical research can bring to the experimental approach. I also discuss the domain of reaction time research, in which Australian mathematical psychology has been particularly influential, and argue that reaction time and accuracy data cannot be understood in the absence of theory.

In some domains of psychology such as perception and decision making, theoretical work is part and parcel of the approach to research. But in cognitive psychology, it often seems that there are continuing threats to the use of quantitative, theory-based methods. Generally, empirical work is little influenced by theory, and old, theoretically inappropriate, and discredited methods are still in routine use. Few graduate programs offer strong modelling or quantitative training, restricting the possibility of quantitative methods being used by new investigators. Jonathan Cohen of Carnegie Mellon University commented recently in a conference talk that Boeing would not design a jet liner based on verbal hypotheses, and certainly the US FAA would not certify such an aeroplane (well, maybe for trans-Pacific routes). If the brain/mind is of at least the complexity of a jet aeroplane, how could it be possible that verbal hypotheses alone would allow us to understand mind and behaviour?

As a specific example, consider the consequences of the fact that research in the field of implicit memory has been driven largely by verbal empirical hypothesis. Until very recently, there has been no theoretically incisive model to explain implicit phenomena or the cognitive processes involved in performing the experimental tasks used to study implicit memories. The accounts given of findings are verbal hypotheses about representation, and these are mainly of the form of dichotomies. The same is true of the findings about implicit memories that have resulted from the use of the brain imaging methods (PET and fMRI) that have recently gained so much publicity and research money. With few exceptions, there has been no effort to link empirical methods, the data they produce, and theory. Often, there seems to be an implicit assumption that there are direct links between experimental variables and the regions of the brain that show patterns of activation corresponding to the variables. The suggestion is that all that is needed to understand cognition is the experimental manipulations and the brain activation patterns they produce. Faced with spectacularly coloured images of brain activation, it is hard not to be seduced. But many important questions are not addressed: what are the circuits involved in information processing, how does processing evolve through time, what computations are being carried out, how is information represented, and so on. These are hard problems, and theory is needed to address them. Currently, in brain imaging and implicit memory research, the concern seems to be only what happens, not how or why (though there are some attempts to use these methods to answer more than the questions based on binary distinctions). This view of implicit memory research is, of course, the extreme view. But an extreme view is well-motivated when the verbal hypotheses of implicit memory research are compared to the recent cumulative trend of theory in explicit memory research (recall and recognition) in which critical tests of older theories have lead to development of new theories that address the problems of the older theories (see McClelland & Chappell, 1998; Shiffrin & Steyvers, 1997).

A practical problem with the empirical approach is that, once the experiments have been done, the approach is mined out and research moves on to another area. Again, implicit memory research provides an example: a large number of experiments were performed to show that there are separate memory systems, one system storing information that can be recalled about past episodes and another system storing information that helps in the perception of previously processed stimuli. The people who were most influential in this work have since moved on to brain imaging research or to research on "false memories". This leaves behind a data base that is crying out for modelling. The key contribution to be made is to produce models that implement hypotheses about processes to explain the repetition effects for repeated stimuli that are observed in data. Examples of the kinds of questions that can be addressed by theory are: to process perceptual stimuli, is a separate memory system needed? If the answer is yes, then how does it operate to facilitate perceptual processing when a stimulus is repeated, and how does the repetition of a stimulus contact the prior episode and feed information back quickly enough to improve perceptual processing (see Ratcliff & McKoon, 1997; Schacter & Tulving, 1994; Schooler, Shiffrin, & Raaijmakers, 1998)?

The implicit memory example suggests how mathematical psychologists can help. What some (of us) mathematical psychologists need to do some of the time is to develop projects in domains that are of importance to empirical psychologists and to make the theoretical modelling approach have an impact on their research that cannot be ignored. One key is to make the importance of the theoretical work transpar-

I thank Stephan Lewandowsky and Gail McKoon for comments on this article. This research was supported by National Institute of Mental Health Grant HD MH44640.
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ently understandable to the empirical psychologists. But this kind of project should be undertaken by only some mathematical psychologists some of the time. A lot of quantitative work is simply not understandable without the necessary mathematical tools. Also, difficult theory needs to be developed whether or not empirical psychologists (or even other mathematical psychologists) understand it.

A domain that requires theory for reasons different from implicit memory is the domain of reaction time. This domain was well represented at the Australasian Mathematical Psychology meeting and historically has been strongly influenced by Australian mathematical psychology. An especially important reason that theory is needed in this domain is that there are multiple dependent variables (correct and error reaction times, the shapes of reaction time distributions, and accuracy values), and the relationship between the variables cannot be interpreted in the absence of a theory that integrates them into a common framework. Given that the responses made in every psychological experiment take time, and many experimental paradigms allow error responses, current theories that ignore the relationship between accuracy and response time are, at best, incomplete. From either a qualitative or an empirical approach, it is quite possible to get one picture of processing if accuracy alone is used to test hypotheses and a different picture if reaction time alone is used to test hypotheses. However, the joint behaviour of accuracy and reaction time is complicated, and no simple qualitative approach provides adequate answers about the joint behaviour of these variables. Fortunately, this is one domain where theoretical progress is being made; there has been a recent convergence across a range of different empirical domain of the classes of theory that account for both reaction time and accuracy (e.g., Audley & Pike, 1965; Busemeyer & Townsend, 1993; Link & Heath, 1975; Ratcliff & Rouder, in press; Ratcliff, Van Zandt, & McKoon, in press; Smith, 1995; Smith & Vickers, 1988; Vickers, 1979).

In conclusion, I point to Estes's (1975) article "Some Targets for Mathematical Psychology", a discussion of the advantages of theoretical models in understanding psychological phenomena. Estes discusses the issues mentioned here as well as how models can provide ways to categorise and understand empirical phenomena that are not apparent directly from data, and how failures of models can lead to cumulative progress in theory. Almost 25 years after that article was published, we can see that mathematical psychology faces almost the same issues as it did in 1975. The difference between now and then is that, in a number of domains, considerable progress has been made in the cumulative development of theory and in the development of experimental methods designed to evaluate and test the theoretical work (two examples in cognitive psychology are memory models and reaction time). The challenge is to make theoretical advances in the newer domains and to make existing theoretical advances impact on empirical psychology.

REFERENCES

Audley, R.J., & Pike, A.R. (1965). Some alternative stochastic models of choice. *British Journal of Mathematical and Statistical Psychology, 18,* 207–225.

Busemeyer, J.R., & Townsend, J.T. (1993). Decision field theory: A dynamic-cognitive approach to decision making in an uncertain environment. *Psychological Review, 100,* 432–459.

Estes, W.K. (1975). Some targets for mathematical psychology. *Journal of Mathematical Psychology, 12,* 263–282.

Link, S.W., & Heath, R.A. (1975). A sequential theory of psychological discrimination. *Psychometrika, 40,* 77–105.

McClelland, J.L., & Chappell, M. (in press). Familiarity breeds differentiation: A Bayesian approach to the effects of experience in recognition memory. *Psychological Review.*

Ratcliff, R., & McKoon, G. (1997). A counter model for implicit priming in perceptual word identification. *Psychological Review, 104,* 319–343.

Ratcliff, R., & Rouder, J.N. (in press). Modelling response times for two-choice decisions. *Psychological Science.*

Ratcliff, R., Van Zandt, T., & McKoon, G. (in press). Comparing connectionist and diffusion models of reaction time. *Psychological Review.*

Schacter, D.L., & Tulving, E. (Eds.). (1994). *Memory systems 1994.* Cambridge, MA: MIT Press.

Schooler, L., Shiffrin, R.M., & Raaijmakers, J. (1998). *A model for implicit effects in perceptual identification.* Manuscript submitted for publication.

Shiffrin, R.M., & Steyvers, M. (1997). A model for recognition memory: REM: Retrieving effectively from memory. *Psychonomic Bulletin and Review, 4,* 145–166.

Smith, P.L. (1995). Psychophysically principled models of visual simple reaction time. *Psychological Review, 102,* 567–591.

Smith, P.L., & Vickers, D. (1988). The accumulator model of two-choice discrimination. *Journal of Mathematical Psychology, 32,* 135–168.

Vickers, D. (1979). *Decision processes in visual perception.* New York: Academic Press.