Research Quarterly for Exercise and Sport

Vol. 79, No. 3, pp. 312–318

Memory Drum Theory's C Movement: Revelations From Franklin Henry

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Franklin Henry's "memory drum" theory of neuromotor reaction (Henry & Rogers, 1960) was one of the most influential studies of the response programming stage of information processing. The paper is the most-cited study ever published in the Research Quarterly for Exercise and Sport. However, few people know there is a noteworthy error in the paper, namely in the description of the C movement, the most complicated of the three responses studied. Henry himself was unaware of the error for nearly 20 years after the paper's publication. The purpose of our paper is to accord the factual record its due respect by revealing the history about the error and its correction. The data are in the form of the original 1960 paper which describes the C movement, a paper by Howell (1953), and personal letters from Henry dating from 1979, when the error was first discovered, and continuing through 1986. In one letter, Henry attributed the error to a mild and specific form of aphasia, manifested by word reversals, from which he suffered throughout his scholarly life. Such a revelation makes the career of this remarkable scholar even more remarkable.

Key words: motor programming, reaction time, research methods, response complexity

A number of papers in motor behavior have had an enormous impact on the field, either because of their contributions to advancing theory in skill development, learning, and control or because of their unique and innovative practical applications. A few examples of such works include Fitts's (1954) mathematical formulation of the speed-accuracy tradeoff, Adams's (1971) closed-loop theory and Schmidt's (1975) schema theory of motor learning, Keele's (1968) treatment of motor programs, Turvey's (1990) paper on coordination, and Haken, Kelso, and Bunz's (1985) contribution to dynamic systems modeling. These classic papers have earned the respect of other workers as indicated by their high citation rates. A search via the Institute for Scientific Information's Web of Science® revealed that as of July 23, 2008, the number of citations for these papers ranged from 358 for Turvey (1990) to 1,387 for Fitts (1954).

The subject of this article is a motor behavior classic: Franklin Henry's paper, with the technical assistance of Donald Rogers, proposing the "memory drum" theory of neuromotor reaction (Henry & Rogers, 1960). This "landmark" (Ulrich & Reeve, 2005) study is the most frequently cited paper ever published in *The Research Quarterly* (now *Research Quarterly for Exercise and Sport; RQES*). Cardinal and Thomas's (2005) recent analysis of the status and contributions of papers published in *RQES* revealed that through 2003, Henry and Rogers (1960) had been cited 328 times. Cardinal and Thomas referred to it as the "citation superstar paper" of *RQ/RQES* (Cardinal & Thomas, 2005, p. S-127). In the 5 years since that analysis, the paper has been cited another 64 times, bringing the total to 392 citations as of July 23, 2008. While this number is considerably lower than each of the other papers mentioned above, except for Turvey (1990), all the comparison articles were published in mainstream psychology journals, making the number of citations for Henry and Rogers (1960) even more impressive.

Submitted: February 27, 2007
Accepted: August 7, 2007

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Clearly, researchers are still interested in this important study. However, it is likely few people are aware of the major error in the paper, namely in the description of one of the three movements (C) that reflected changes in the complexity of the responses. That error would render the Henry and Rogers (1960) experiments impossible to replicate using the same apparatus and movements. It went undetected for nearly 20 years after the paper's publication; Henry himself was unaware of the error. We have nothing but the utmost respect and admiration for Henry and his contributions as the "father" of motor behavior research. Our purpose here is to accord the factual record its due respect by revealing the history about the error and its correction. We believe this is what Henry would have wanted.

The Henry and Rogers (1960) study was one of the most influential of the response programming stage of information processing. This stage follows stimulus identification and response selection/translation stages. It is the final stage prior to response initiation, during which the details of a stored neuromotor program are retrieved from memory and channeled into the efferent outflow leading to movement. Prior to Henry and Rogers (1960), most of the interest in information processing concerned the stimulus identification and response selection/translation stages and involved relatively simple movements. The Henry and Rogers study was the first to investigate the specific nature of the movements to be made and how differences in the complexity of rapidly executed large scale arm movements would affect the reaction time (RT) to initiate them. An important prediction from the theory was that a more complex movement (defined as the number of movement parts comprising the response) would require more time to initiate, because a more comprehensive stored program would need to be retrieved from memory and directed to the appropriate motor neurons and muscles. Thus, the simple RT to initiate a large-scale movement should increase as a function of the movement's complexity.

We briefly review the Henry and Rogers (1960) article, with emphasis on describing the three movements used in their study. We show how their description of one (Movement C) is incompatible with an apparatus from Howell (1953), which was the source for the 1960 experiments. Next we reveal how Greg Anson, a doctoral student in Robert Christina's Motor Behavior Laboratory at The Pennsylvania State University, discovered the error in 1979. The story continues with a series of letters between Henry, Anson, Christina, and Mark Fischman, who was also a doctoral student in Christina's laboratory from 1979 to 1982. The correspondence began in 1979, continued through 1986, and includes a remarkable disclosure from Franklin Henry that may help to explain the reason behind the error in Movement C.[1] We believe our paper has as much to do with research methods and scientific protocol as it does with motor programming theory, and we conclude with some comments regarding the importance of replication in science.

The 1960 Paper

Henry and Rogers (1960) conducted two experiments involving male and female participants ranging in age from 8 to 35 years. Both experiments used a simple reaction time (SRT) paradigm, in which the participants knew which response to make on any given trial. The auditory stimulus was constant in all conditions, as were the response alternatives. The apparatus consisted of a reaction key, two suspended tennis balls, and a dummy push button. Three movements (A, B, and C), differing in complexity, were studied. Each movement began with the participant lightly depressing the reaction key with his or her finger. Because an accurate description of the movements is crucial, we describe them verbatim from Henry and Rogers (1960, p. 452):

> Movement A—When being tested with Movement A, the subject simply lifted his finger a few millimeters, which permitted the reaction key to open and stopped the chronoscope.
> Movement B—Movement B was more complicated. A tennis ball hung by a string which placed it about 15 cm. above the reaction key and 30 cm. further back, away from the subject. In response to the stimulus signal, he reached forward to grasp the ball. When the ball was touched, the upper support end of the string pulled out of a switch clip, thus freeing the ball to permit a follow through.
> Movement C—Movement C was somewhat more complicated; it included a series of movements and reversals. A second tennis ball (C), also supported by a string and clip, was hung 30 cm. to the right of ball B. In response to the stimulus, the subject moved his hand from the key, reaching forward and upward to strike ball C with the back of the hand, then reversed direction to go forward and downward, touching a dummy push button on the baseboard to the left of the reaction key, and finally reversed again to go upward and forward, striking down ball B.

We will show that certain portions of the Movement C description are essential to understanding the error in the 1960 paper.

Results from Henry and Rogers (1960) revealed that SRT increased significantly from Movement A to B, and then again from Movement B to C, giving rise to the classic response complexity effect (for a review of the many studies supporting this effect, see Christina, 1992). Although subsequent research has found that accuracy demands and/or difference in anatomical units (e.g., finger vs. whole arm) rather than movement complexity per se may provide a better explanation for the SRT increases found by Henry and Rogers (e.g., Anson, 1982, 1989; Fischman & Mucci, 1990; Fischman, Yao, & Reeve, 2000; Gordon & Christina, 1991; Short, Fischman, & Wang, 1996; Sidaway, 1991; Sidaway, Christina, & Shea, 1988; Sidaway, Sekiya, & Fairweather, 1995; Smiley-Oyen, Lowry, & Kerr, 2007; Smiley-Oyen & Worringham, 1996), the impact of Henry and Rogers (1960) on this area is not diminished.

The Error in Movement C Description

Early in 1979, Greg Anson was working on his doctoral dissertation in response programming, and part of his preliminary work involved an attempt to replicate the Henry and Rogers (1960) experiment. We acknowledge that the exact apparatus used in one study does not have to be used to replicate a set of experimental findings. It is essential that any important set of findings is robust enough to emerge in situations other than the exact ones used in the original experiment, and, in fact, this was demonstrated in the studies cited. However, in Anson's dissertation work (Anson, 1982), exact replication (i.e., "In scientific research, the repetition of an experiment to confirm findings or to ensure accuracy," *American Heritage Dictionary of the English Language*, 2003) was important theoretically, because it engaged two significant questions. The first addressed motor programming and whether adding elements (i.e., increasing the number of connected movement parts) was sufficient to require more motor preparation time. The second asked whether the SRT effects found by Henry and Rogers (1960) could have been due to biomechanical/anatomical factors rather than increases in programming time as a function of increases in response complexity. For example, one must overcome greater inertia to initiate movement of an entire limb rather than a finger in reaction to a stimulus. Initiating the three Henry and Rogers movements was not standardized, suggesting that biomechanical factors could have been responsible for the SRT increases that were found. Klapp's (1978) review of reaction time and programmed control strongly informed these questions and represented a "strong inference" approach to testing alternative hypotheses (see Platt, 1964). To test hypotheses regarding these peripheral, nonprogramming elements, it was essential that Anson use an exact replica of the apparatus used by Henry and Rogers (1960).

In reconstructing the apparatus, Anson noticed a discrepancy in the placement of the dummy push button, which was the target for the second component of Movement C. Henry and Rogers (1960, p. 452) directed the reader to a paper by Howell (1953) for an illustration and detailed description of the two-ball apparatus. However, as shown in Figure 1, Howell's (1953) diagram placed the dummy button to the *right* of the reaction key, while Henry and Rogers' (1960) description placed it to the *left* of the reaction key. In addition, after reaching forward and upward to strike ball C, the second component required a reversal of direction to go *forward and downward* to touch the dummy button. Again referring to Howell's (1953) illustration, these instructions do not make sense. So, Anson was faced with two problems in attempting to reconstruct the Henry and Rogers apparatus. He wrote to Henry (May 17, 1979) and asked for clarification and received a reply dated May 21, 1979, which opened:

> Dear Mr. Anson: I am ashamed to have published an apparatus description in the 1960 Memory Drum paper that contains some inexcusably careless errors. Probably the reason (*not* excuse) is that I did not re-read that part carefully because my attention was centered on the more substantive parts of the MS. Here is the correct description....

The rest of the letter (one page, typed single-spaced) explicitly described the 1960 apparatus, including dimensions and locations of all components. The description was based on examination of the actual apparatus, which Henry still had in his lab. Essentially the reaction key, ball B, ball C, and dummy button formed the four corners of an 8-inch [20.32 cm] square, and the ball

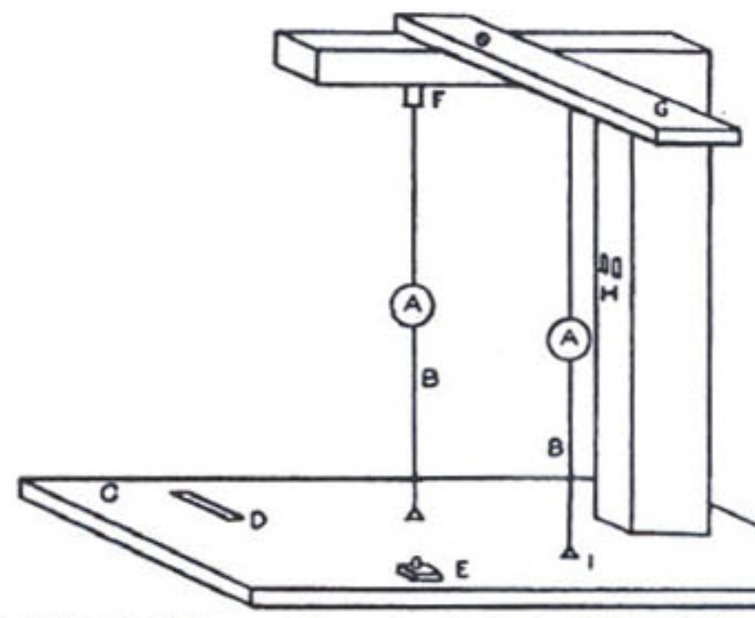

FIG. 1. Speed of Movement Apparatus. A—tennis ball; B—48 lb. nylon cord; C—base board; D—reaction key; E—push button; F—friction contacts; G—side arm; H—signal lights; I—cord holder.

Figure 1. Illustration of the Howell (1953) apparatus, which Henry and Rogers (1960) referred to as the source for their experiments.

centers were 6 inches [15.24 cm] above the base. For the 1960 experiments, the positions of Howell's (1953) dummy button and ball C were exchanged. Thus, the description of Movement C as given in Henry's letter to Anson was the following:

> In response to the stimulus, the subject moved his hand from the key, reaching rightward and upward to strike ball C with the back of the hand, then changed direction to go forward and downward, touching a dummy pushbutton on the baseboard to the right of the reaction key, and finally reversing to go upward and leftward, striking down ball B with the open palm of the hand. The air distance moved would be about 3 x 27 = 81 cm, less 6 cm for two ball radii. This included one directional change of 45° plus one direction reversal.

The Corrected "Memory Drum" Apparatus

Following receipt of Henry's letter, Anson was still uncertain about the exact placement of tennis balls B and C. The uncertainty was because a ball height of 6 inches (15.24 cm) above the baseboard would have resulted in approximately a 37° direction change in moving from ball C to the pushbutton, and then again from the pushbutton to ball B. A height of 8 inches (20.32 cm) would satisfy the requirement for a 45° directional change. So Anson wrote to Henry (May 31, 1979) requesting clarification and enclosed a scale model of the response pattern for movement C. The model was made of graph paper, which unfolded to form a three-dimension model of the exact paths of the movement components of the C response. Anson asked:

> Could you tell me if the location and direction of the movement components is [*sic*] correct and if the orientation of the reaction key and ball C is parallel to the front of the table on which the apparatus would be mounted?

One week later (June 7, 1979), Anson received a reply from Henry stating:

> The model you sent is correct. As to the 45° direction change, I should have said approximately 65°. If you will imagine a tilted plane whose base rests on the diagonal between start and dummy button, and passes through C, calculations via trig. gives a directional change of 68.899° if I have made no numerical errors. But that is based on the minimal distance between the points—moving as fast as possible the subject will move on a somewhat curved path with your path 1 as the chord, and will similarly curve outside with your path 2 as the chord, on the way to touch the dummy button. Thus 65° is my somewhat subjective estimate of the actual direction change.

Armed with these explicit details from Henry, Anson constructed the "Memory Drum" apparatus (see Figure 2) for his dissertation research (Anson, 1982, Experiment 1) and successfully replicated the findings of Henry and Rogers (1960). However, he also found that alternative explanations, such as differences in anatomical units and differences in accuracy demands, could account for the SRT differences between the Henry and Rogers A and B movements (Anson, 1982, Experiment 2). This apparatus was also used in a number of subsequent studies from The Pennsylvania State University laboratory (Christina, Fischman, Lambert, & Moore, 1985; Christina, Fischman, Vercruyssen, & Anson, 1982; Christina & Rose, 1985), all of which supported the hypothesis that response programming time is a function of the number of connected movement parts of a response (i.e., the response complexity effect).

Following these events, Henry wrote a chapter in *Perspectives on the Academic Discipline of Physical Education* in which he detailed the historical evolution of the memory drum theory (Henry, 1981). In that paper, the error in Movement C was corrected, and the description was exactly as Henry had instructed Anson:

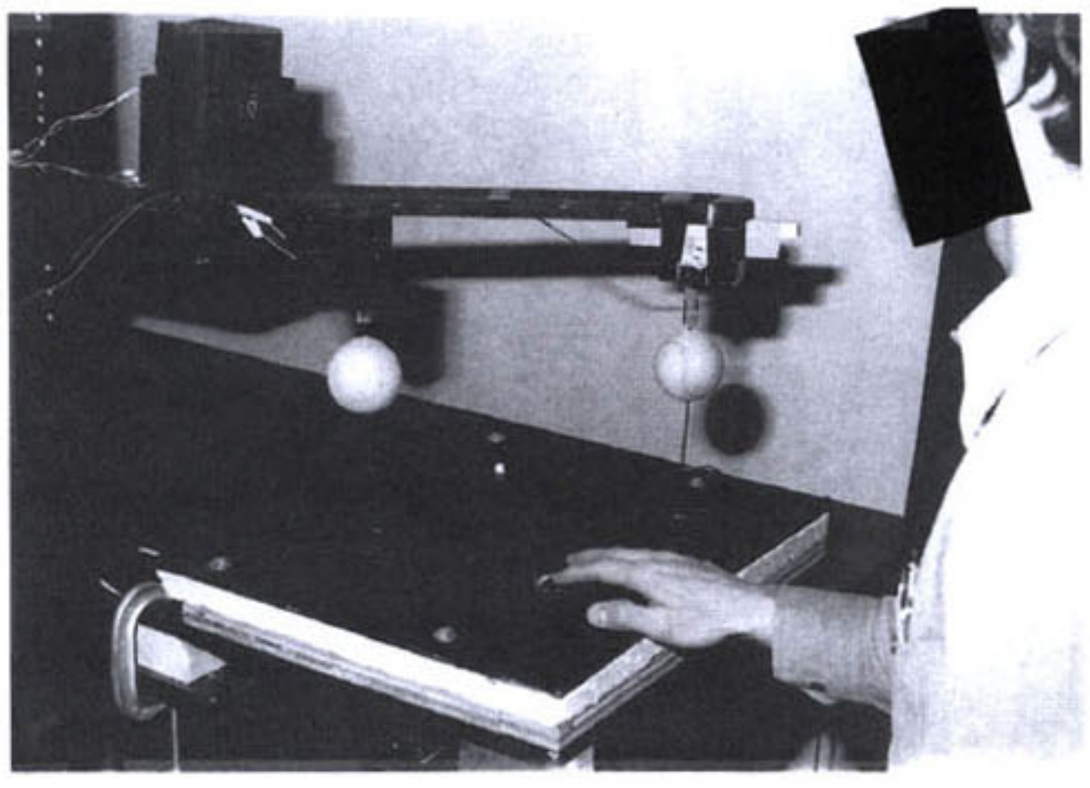

Figure 2. Photo of the The Pennsylvania State University memory drum apparatus that was constructed based on instructions from Franklin Henry.

Movement C may be described as follows: The subject sits at a table, with the right index finger resting on a sensitive reaction key. There are two tennis balls, each hanging on a string which holds them 6 in. (15 cm) above the table top. At the signal, the hand is moved diagonally upward and to the right to backhand the first ball and continue diagonally downward and forward to slap a button target on the table top, and then move diagonally upward and to the left to snatch the second ball before slowing down (p. 305).

Henry provided a less-detailed description of Movement C, also corrected, in an autobiographical chapter (Henry, 1992). Unfortunately, even with published corrections of the 1960 error, several texts in motor control and learning continue to use the erroneous Henry and Rogers (1960) description (e.g., Coker, 2004; Magill, 2007; Schmidt & Lee, 2005; Schmidt & Wrisberg, 2004).

The Reason for the 1960 Error: Henry's Disclosure

Between February 1983 and April 1986, Henry and Fischman developed a correspondence during which they exchanged 18 letters, 13 of which Henry initiated. He served as an "unofficial" reviewer of Fischman (1984), who used a target-striking task to test predictions from the memory drum theory, and reviewed early drafts of an extended practice study that also tested predictions from the theory (Fischman & Lim, 1991). Henry's comments were incredibly detailed and thorough, often providing a lengthy historical treatment of the topic under discussion. When deserved, Henry was quick to compliment, but more often than not he was a stern critic. His feedback was substantive, as opposed to cosmetic, and no doubt improved the final products. His review of Fischman (1984) was six pages typed single-spaced. However, he also had a biting sense of humor, as displayed in an August 7, 1985, letter. Henry was not pleased with some of Fischman's wording (1984) and wrote:

> Fortunately, your 1984 paper comes through without getting into difficulty except for two spots, both on p. 406 . . . (I was tempted to say "Except for two flaws" instead of two spots. Just be thankful that you were not required to enroll in my Thursday seminar. According to legend, the janitor had to pump the blood out of the floor drain on Friday mornings.)

The critiques of research papers were not unidirectional; Henry sought Fischman's feedback on his final published paper (Henry, 1986) as well as a short manuscript submitted to the *Journal of Motor Behavior* in April 1986. The manuscript, which was never published, was titled "On the Relation Between Response Duration and Reaction Latency." Henry's manuscript referred to a large increase in simple RT in a study by Quinn, Schmidt, Zelaznik, Hawkins, and McFarquhar (1980). However, as Fischman pointed out in an April 10, 1986, letter to Henry, the Quinn et al. experiments used choice RT. In the final letter between Henry and Fischman (April 17, 1986), Henry revealed the following:

> . . . I did know that they used choice RT. I must have read the MS carefully at least 10 or 12 times without catching it. I live in constant fear of making that type of error. During my entire scholarly life I have suffered a mild and specific form of aphasia, namely the use of an apposite word; it just sounds or reads OK. (In clinical aphasia, the first symptom to appear is a reversal of gender, usually). While my reversals have usually been corrected before printing, my psychologist friend and colleague Rheem Jarrett brought to my attention just last year that in my 1960 "memory drum" paper, p. 452, 6th line from the bottom, I said ". . . reversed direction to go *forward* and downward. . . ." instead of *backward*. No wonder the Penn State Gang was confused as to the movement C that I used!

What a remarkable revelation. Did others know of Henry's aphasia? Roberta Park, a long-time friend and colleague of Henry's, knew (R. J. Park, personal communication, April 15, 2005), but understandably chose not to include it in her glowing tribute to Henry's career following his death (Park, 1994). We suspect that Rheem Jarrett also knew, but we have no direct evidence to support this speculation.

Lessons Learned and Postscript

One might think a mild form of aphasia, such as Henry's, is not a serious condition; it certainly pales in comparison to many others. Some with aphasia cannot communicate at all; others are frustrated by their errors, while others just move along and accept it. However, to one whose scholarly life depends on precision and clarity, both in thought and word, such a condition can be debilitating. Perhaps this also says something about the expectations we have of colleagues. Henry's career spanned nearly half a century and included over 120 published works (Park, 1994), plus the training of

many doctoral students who went on to become productive scholars and mentors of their own students (see Montoye & Washburn, 1980; Thomas, 1997). To have accomplished that while constantly laboring under the burden of aphasia, we believe, makes the career of this remarkable scholar even more remarkable.

Without a doubt, Henry's legacy in motor behavior, and more generally in the larger field of kinesiology, is pervasive. His influence is not diminished by the error in the memory drum theory paper. The discovery of an error, attributable to a neurological condition, in a lifetime of exemplary scholarship in no way renders Henry "disabled." It may be suggested that, as humans, we are all capable of making mistakes; some may have to work a little harder than others to prevent them.

Perhaps the most important lesson from this story is the necessity for replication in science. It ensures that we move forward with fewer misconceptions and greater understanding. In this paper, we acknowledge two important scientific principles: (a) generalizing the findings of a specific experiment to different contexts, and (b) performing an exact replication of another's work. With respect to Henry and Rogers (1960), many had followed the first principle, but none had followed the second. To test his alternative accounts for the SRT differences as a function of response complexity, Anson (1982) had to apply the second principle. Science advances by generating multiple alternative hypotheses for a phenomenon and devising crucial experiments to exclude one or more of the hypotheses. Readers interested in this "strong inference" approach will be familiar with the classic papers by Popper (1959) and Platt (1964) and should consult a contemporary philosophy of science article by Davis (2006). The strong inference approach revealed a significant error in one of the most important papers in our field. Thus, even the giants on whose shoulders we stand are not infallible. To rigorously question and verify is essential. We believe Henry would agree.

As a final comment, Henry was interested in sharing the story behind the mystery of Movement C, which would have revealed his aphasia. In fact, in 1986, Henry and the present authors agreed to jointly author a paper on the topic. Henry volunteered to take the lead and write a first draft; however, he experienced a number of unfortunate personal circumstances, and the project never got underway. So 20 years later, out of respect for Henry and the factual evidence, we bring the story to the attention of the scientific community.

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Note

1. The original correspondence is available for inspection from Mark Fischman at Auburn University and from Greg Anson at the University of Otago.

Authors' Notes

Portions of this paper were presented at the 2006 meeting of the American Alliance for Health, Physical Education, Recreation, and Dance, and the 2007 meeting of the North American Society for the Psychology of Sport and Physical Activity. We thank Jim Cauraugh and two anonymous reviewers for their helpful comments on a previous version of the manuscript. Please address all correspondence concerning this article to Mark G. Fischman, Auburn University, Department of Kinesiology, Auburn, AL 36849.

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