DISSERTATION

THE ROLE OF CHUNKING AND AWARENESS IN SERIAL LEARNING: AN INVESTIGATION USING THE HEBB DIGITS TASK

Submitted by

Geoffrey O'Shea
Department of Psychology

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY GEOFFREY O'SHEA ENTITLED THE ROLE OF CHUNKING AND AWARENESS IN SERIAL LEARNING: AN INVESTIGATION USING THE HEBB DIGITS TASK BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Vicki J. Volbrecht

Patricia L. Davies

Benjamin Clegg
Adviser

Carol A Seger
Co-Adviser

Department Head/Director

ABSTRACT OF DISSERTATION

THE ROLE OF CHUNKING AND AWARENESS IN SERIAL LEARNING: AN INVESTIGATION USING THE HEBB DIGITS TASK

The Hebb Digits task, an incidental serial learning procedure first introduced by Donald Hebb (1961), has been useful for elucidating the mechanisms by which sequential information is transferred from short-term to long-term memory. The work presented in this dissertation is an attempt to develop a perceptual processing account for how learning occurs in the Hebb Digits task. Chapter One reviews the scope of influence that the Hebb Digits task has had on researchers investigating memory processes including theoretical accounts of how learning occurs in the Hebb Digits task, the evidence for implicit learning in the Hebb Digits task, and the relationship of these ideas with the original theories of Hebb. Chapter Two presents findings in support of the perceptual processing account based on experiments demonstrating the dominance of perceptual chunking, compared to motor chunking, on Hebb Digits learning. Chapter Three presents the findings from an experiment testing whether the dominance of perceptual chunking in Hebb Digits learning is due to an increase in awareness for the incidental elements of the task. Although the results of Chapter Three failed to support the hypothesis that perceptual chunking increases awareness, the pattern of findings indicates that after awareness of sequence repetition is accounted for, there is no identifiable impact of chunking on Hebb Digits learning.

Additionally, the results of a regression analysis reveal that Hebb Digits learning is mediated by awareness of sequence repetition via recall and verbal measures. Based on the findings in this dissertation, it is hoped that researchers will better understand the mechanisms influencing performance in this important task for probing the juncture at which information is transferred from a short-term trace to a long-term structure.

Geoffrey O'Shea
Psychology Department
Colorado State University
Fort Collins, CO 80523
Summer 2005

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DEDICATION

This Ph.D. dissertation is dedicated to the memory of my father, William George O'Shea (1931-2001), whose wisdom and guidance always gave me insights into life and whose everlasting love will always give me hope.

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CHAPTER ONE

SERIAL LEARNING AND THE HEBB DIGITS TASK

It has long been recognized that the performance of a wide range of mental and motor activities is based on the capacity to encode and represent the temporal ordering of a series of stimuli (Ebbinghaus, 1902; Hirsch, 1959; Lashley, 1951; for a review, see Crowder & Greene, 2000). For example, remembering a telephone number or starting a car requires the ability to mentally sequence a series of items or steps in a particular order. More hierarchical abilities involving the development of proficiency at a skill, such as playing the piano, also require adherence to a temporal structure, in this case stressing the coordination of thought processes and movements. Such a capacity is known as serial learning.

One of the interesting aspects of serial learning is that it can take place both with conscious intention, as when we deliberately rehearse a phone number in order to commit it to memory, or without conscious intention as when we gradually acquire memory for a phone number simply by dialing it often. This latter form of memory acquisition is termed 'implicit learning' and has been formally demonstrated in a number of studies (Nissen & Bullemer, 1987; Reber, 1967; Stadler, 1993; for a review see Seger, 1994). The identification of different conscious and unconscious learning processes have led to attempts to relate the level of consciousness involved in a learning experience to the operation of particular memory (Craik & Jacoby, 1975;

Tulving, 1985) and brain (Clark & Squire, 1998; Cotterill, 2001; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Shastri, 2002) systems. In other words, the degree of conscious awareness for the information learned in a given task develops based on the memory system or brain region used to process this information.

One of the primary ways in which serially-ordered information is learned, whether the mode of acquisition be explicit or implicit, is through chunking or the reorganization of a large quantity of information into smaller segments. For example, memorization of a long string of digits, such as 837246195, can be facilitated if this string is recoded into three groups such as 837-246-195. Chunking has been identified as a beneficial process for retaining information due to the limited storage capacity of short-term memory (Miller, 1956). The phenomenon of chunking is ubiquitous in research on cognitive processes appearing influential in a wide variety of contexts from studies on number processing (e.g., Fendrich & Arengo, 2004; Klemmer, 1959; Severin & Rigby, 1963), recall (Bower & Winzenz, 1969; Winzenz & Bower, 1970), motor learning (Verwey, 2003a, 2003b; Verwey & Dronkert, 1996), incidental learning (Koch & Hoffman, 2000; Stadler, 1993) and the effects of rehearsal rate on chunking (Zhang & Simon, 1985; Yu, Zhang, Jing, Peng, Zhang, & Simon, 1985). Not surprisingly, chunking is also a primary feature in a number of models attempting to explain the representation of serially-ordered information in short-term memory. For example, some theorists have suggested that serially organized information becomes represented in memory as chunks based on the strength of associations between adjacent items (Estes, 1972; Lee & Estes, 1977, 1981; Shiffrin & Cook, 1978). Still, more comprehensive models of serial learning have been proposed on the basis of a distributed memory system where serial order is represented by a constellation of associative chunks of information rather than connections between specific items (Murdock, 1982, 1983).

If chunking can boost the short-term retention of information, does it also increase the level of awareness for the information being learned? When one considers that chunking results in the restructuring of serial information into a more hierarchical form, it suggests that chunking represents the use of top-down processes or a conscious strategy on the part of the learner. However, there is some evidence that chunking can be a subjective process that emerges spontaneously during serial learning (McLean & Gregg, 1967; Bower & Springston, 1970) and as noted above chunking is commonly seen in implicit learning tasks which would seem to suggest that it is occurring without conscious intention. The extent to which a given implicit learning task is purely implicit is a debatable issue (Perruchet & Amorim, 1992; Shanks & Johnstone, 1998; Shanks & St. John, 1994; Stadler & Roediger, 1998; St. John & Shanks, 1997). For example, some participants in an implicit learning task may acquire conscious knowledge of the structure used in the task and thus, be able to predict the occurrence of the critical stimuli. In fact, subjects in a number of implicit studies have reported developing conscious knowledge of the structure of the task that has facilitated their learning (Cleeremans & McClelland, 1991; Hartman, Knopman, & Nissen, 1989; Hoffman & Koch, 1998; Perruchet & Amorim, 1992; Willingham, Nissen, & Bullemer, 1989). These findings suggest that chunking can not only facilitate learning in an implicit task, but can also lead to awareness of the underlying structure of the task (Koch & Hoffman, 2000). Along these lines, it is interesting to note that Schlaghecken, Sturmer, & Eimer (2000) have reported a relationship between the electrophysiological activity of the brain, as measured by event-related potentials (ERPs), and the acquisition of explicit knowledge about the underlying structure of an implicit task through chunking. Thus, it appears that chunking may not only be an important process in serial learning, but part of the effect of chunking may be to increase awareness of the structure of the information being learned.

If chunking and awareness do interact during learning, what process or processes account for this interaction? Is it possible that the transfer of information from short-term to long-term memory subsequently results in the development of awareness for this information? In one of the leading theories of memory, the working memory model (Baddeley, 1986), chunking is considered an important mechanism contributing to the ease with which information can be rehearsed, and thereby retained, in short-term memory (Baddeley, 1990). Interestingly, Baddeley has recently extended his working memory model with an account of how awareness is an important process for the retrieval of information from long-term memory (Baddeley, 2000). Indeed, other theorists consider that conscious processes are very important in the operation of working memory (Baars, 2003; Baars & Franklin, 2003). Yet, despite separate acknowledgement of the importance of chunking and awareness in working memory, Baddeley's model lacks any formal description of how chunking and awareness interact to transfer serially ordered information from short-term to long-term memory. In fact, several theoretical models exclusively devoted to serial learning also fail to incorporate accounts of how the interaction between chunking and awareness may affect the long-term representation of serially-ordered information (e.g., Nairne, 1990, 1991, 1992; Nelson, 1971). It is, thus, an important theoretical challenge to develop an understanding of the relationship between the chunking of serially ordered information and consciousness in long-term learning.

One procedure that has been used in separate studies examining the role of chunking (Bower & Winzenz, 1969; Nelson, 1971) and consciousness (Baddeley & Warrington, 1970; McKelvie, 1987) in the long-term representation of serially ordered information was introduced by a student of Karl Lashley's, Donald Hebb (1961).[1] The procedure for the Hebb Digits task is deceptively simple. A series of nine digits (various permutations of the numbers from 1-9; e.g., 824537916) are presented individually at a rate of 1 digit/sec to participants who must repeat this series back in the same order from memory. This procedure is repeated for 24 trials. Participants are, therefore, engaged in a short-term memory task. However, unbeknownst to participants, an identical series of 9 digits is continually presented on every third trial. The repeated exposure to this reoccurring 9 digit series enables participants to learn these digits. As a result, comparisons of performance on the repeated series with the new or novel series of digits that occur on the intervening trials appear to suggest that participants recall significantly more of the digits in the repeating series compared to the novel series. Thus, on the surface, the Hebb Digits task appears to be a short-term memory task, but the presence of the repeated digit series adds a long-term memory component to the task.

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[1] Karl Lashley (1951) was one of the first theorists to argue for an account of serial learning based on a more hierarchical organization of processes rather than a mechanism utilizing a simple pairwise associative learning of adjacent items. Lashley's ideas are still consider relevant in modern work on serial learning (Bruce, 1994).

The Hebb Digits task has been an important tool for researchers to probe the characteristics of human memory. For example, performance on the Hebb Digits task has been taken as evidence that short-term and long-term memory processes are dependent on the same unitary memory system (Melton, 1963). More specifically, the transfer of digit sequences from short-term to long-term memory has been found to be based on an all-or-none process rather than the gradual learning of individual elements of the sequence (Nelson, 1971; Cumming, Page, & Norris, 2003). More recently, computer models of associative memory have been proposed using Hebb Digits performance as a source of long-term memory for the temporal ordering of events (Burgess & Hitch, 1999; Lewandowsky & Murdock, 1989). As previously mentioned, the omission of an account of the long-term representation of serial information from Baddeley's (1986) influential model of working memory suggests that an improved understanding of the mechanisms responsible for the Hebb effect would contribute to developing a deeper understanding of how information is transferred from a transitory state to a more lasting representation in memory.

Although evidence of learning in the Hebb Digits task appears to be fairly straightforward-recall for the repeated digits should be greater than the non-repeated digits-researchers have actually used a number of modifications of this basic approach. The following sections present a review of the Hebb Digits task that focuses on both the empirical and theoretical aspects of learning in this paradigm. In particular, the various methods that have been used to score digit recall are surveyed with the goal of determining which of these methods lead to the most useful theoretical accounts of learning performance.

Assessing Recall Performance in the Hebb Digits Task

Hebb (1961) initially demonstrated greater learning for the repeated series compared to the novel strings of digits by showing a linear increase in the number of participants who perfectly recalled the repeating series of digits across the 24 trials. In contrast, there was no systematic linear trend for perfect recall of the novel strings of digits across the 24 trials. Hebb, thus, considered learning of the repeated string to have occurred since more participants could recall that string perfectly than the novel strings by the 24th trial. In the following section, we will review the various methods that have been used to assess digit recall and the extent of learning in the Hebb Digits task.

Methods of scoring digit recall. When a participant repeats back the digits on a given trial, it is often the case that mistakes will occur in recall. A common type of mistake is for participants to deviate from the original presentation order of the digits. Therefore, instead of repeating the digits back in their correct positions, participants will insert an incorrect digit into one of the other serial positions. These insertions may sometimes involve inserting a digit that occurred later in the sequence into an earlier position or vice versa. Furthermore, participants may transpose two adjacent digits. Another type of mistake that is often observed is that participants may omit digits from the sequence or recall fewer than the number of presented digits. In such instances, participants may recall the sequence in fragments demarcated by the omitted digits. Thus, based on the pattern of recall errors that are exhibited by participants, it is a difficult issue to assess recall performance across a group of participants. For example, do transposition errors involving adjacent digits represent a greater level of recall than errors in which earlier and later digits in the series are transposed? Recall performance in the Hebb Digits task, thus, depends on the view adopted by researchers of how to score the errors committed by participants.

The methods that have been used to assess recall performance in the Hebb Digits task can be divided into two categories: conservative measures and liberal measures. One conservative measure that has been used by some researchers is the number of participants who recall the digits perfectly on a given trial (Bower & Winzenz, 1969; Hebb, 1961; Melton, 1963). Another conservative method of scoring recall performance is using a strict serial recall criterion or examining the mean number of digits recalled in their correct position from left to right (Baddeley & Warrington, 1970; Bower & Winzenz, 1969; Caird, 1964; Cumming, Page, & Norris, 2003; Hughes & Jones, 2003; Melton, 1963) Additionally, researchers have scored recall according to the mean number of digits correctly recalled up until the first error (Cohen & Johansson, 1967; Hebb, 1961). Such an analysis focuses on participants' recall for the initial items presented or the primacy effect. This variation of the left-to-right method may not provide a complete account of the degree to which participants have recalled a given sequence as it ignores the recency effect in retrieval or the improved recall performance for the most recently studied items or the last digits that were presented (Watkins & Watkins, 1977). However, the primacy effect may be more strongly linked to the retrieval of information from long-term memory than the recency effect and thus, may be a more accurate indicator of the extent to which the repeating sequence has been represented in long-term memory.

Although assessments of the number of perfectly recalled trials and correct serial position from left to right might seem like intuitive methods for scoring digit recall, participants' recall behavior often deviates widely from the manner of digit presentation. For example, participants may recall only seven digits rather than nine. Conversely, participants may recall 10 or 11 digits rather than the nine that were presented. Within these deviations from nine digit recall, participants may recall only fragmented sequences of the original nine digits. As a result of participants' propensity to deviate from a strict adherence to a nine digit recall format, there are additional scoring measures for the Hebb Digits task that take into account such deviated recall performance. Such measures might be considered to be liberal scoring procedures. Accordingly, some researchers have developed a composite scored based on the mean number of digits that participants recall from left to right up until the first error made and then the mean number of digits recalled from right to left up until the first error made in this direction (Bartz, 1969; Schwartz & Bryden, 1971).

In a review of the above scoring methods for the Hebb Digits task, McKelvie (1987) recommended a comprehensive procedure that integrated a number of commonly used scoring techniques. Specifically, McKelvie's method scores recall performance in four parts: a) number of digits correctly recalled from left to right up until the first error, b) number of digits correctly recalled from right to left up until the first error, c) number of correct fragments of two or more correctly recalled between and including the two errors, and d) the number of digits correctly recalled in their exact position not including digits already counted as correct. For example, McKelvie presents the case where a participant is presented with the digit sequence

591637824 and responds with the sequence 5936784. Analyzing the participant's response yields the score 2 (number of digits in the correct order from left to right up until the first error), plus 1 (number of digits in the correct order from right to left up until the first error), plus 2 (number of correct digit fragments between the first error from left to right and the first error from right to left not including digits already counted as correct), plus 1 (number of digits in the exact position that have not previously been counted as correct) for a total recall score of 6. Conversely, a strict left to right analysis of the above response would yield a total recall score of 3. Thus, McKelvie's scoring method is more sensitive to fragments and as a result, produces more liberal recall scores than the left to right analysis when participants are recalling sequences in fragments. However, McKelvie's scoring method and the left-to-right method are likely to produce equivalent scores when digit recall more closely adheres to the original order of the sequence.

Methods of assessing learning. In addition to the various methods used to score recall performance in the Hebb Digits task, there are also a number of methods used to assess learning in the Hebb Digits task. As mentioned previously, learning in the Hebb Digits task is based on greater recall for the repeated series of digits compared to recall for the novel or random strings of digits.

One systematic technique for assessing learning in the Hebb Digits task involves examining cumulative learning across the entire task (Bower & Winzenz, 1969; Cohen & Johansson, 1967; Cumming, et al., 2003; McKelvie, 1987; Schwartz & Bryden, 1971; Winzenz & Bower, 1970). While some of these researchers (Bower & Winzenz, 1969; Cohen & Johansson, 1967; Winzenz & Bower, 1970) have simply compared mean recall for the repeating compared to the random series across all the trials, other researchers (McKelvie, 1987; Schwartz & Bryden, 1971) have sought a more detailed approach dividing the 24 experimental trials into 8 blocks with each block consisting of 1 repeating trial and the 2 surrounding novel trials, the one immediately preceding and the one immediately following the repeating trial. In this type of analysis, performance on each block is assessed by comparing the number of participants who perfectly recalled the repeating digits (R) to the mean number of participants who perfectly recalled the digits on the two novel trials (N). Thus, Block 1 would consist of a comparison of performance on Trial 3 (the first occurrence of the repeating trial) with a comparison of performance on Trials 2 and 4 (the two surrounding novel digit strings). A corrected score for each block is then computed by subtracting the number of participants who demonstrated perfect recall on the novel trials from the number of participants who demonstrated perfect recall on the repeating series (R – N). The corrected scores across the blocks are then analyzed using ANOVA and post hoc tests for linear trends to demonstrate that participants gradually learned the repeating sequence across the blocks. A slight variation of the above approach was used in a recent study by Cumming, Page, and Norris (2003) who used least-squares linear regression to compare performance for the repeating series (lists 3, 6, 9, etc.) with performance on the immediately preceding random series (lists 2, 5, 8, etc.). Finally, Cumming et al. analyzed the slopes of the regression lines for improvement in recall for the repeating series using a paired-sample t-test.

The empirical assessment of learning in the Hebb Digits task can also be examined using analyses of performance on Block 8 or the final three trials. This type of analyses is predicated on the assumption that greater learning of the repeated series compared to the novel series should have occurred by the completion of the task. Moreover, analyses of Block 8 performance as the criterion for learning also make the assumption that participants will exhibit their most complete learning of the repeated sequence on the final trial. This assumption is based on the underlying theoretical explanation of Hebb Digits task performance, namely that by the end of the task, a long-term representation of the repeating digits series should have developed so that recall of this repeating series should be greater than a novel digit series. However, the restriction of learning to the level of performance exhibited on the final trial may not take into account uncharacteristic performance errors that may occur on this final trial. Thus, despite the statistical problems associated with reliance on the performance of a single trial for assessing learning, performance on Block 8 avoids individual differences in the rate of learning that may occur throughout the earlier blocks when learning of the repeated digit sequence may be incomplete. The assessment of learning through the analysis of only Block 8 has, so far not been used by any researchers.

Thus, cumulative learning of the repeating series in the Hebb Digits task can be assessed by examining performance across the entire task or simply by assessing performance on the final three trials. These analyses have in common the idea that recall performance on the repeating series in the Hebb Digits task should culminate in greater learning of the digits than performance on the random series of digits. However, it should be noted that such an analysis is reliant on a single data point (i.e., performance on the final repeating sequence) which can be statistically problematic when one considers that a participant, despite having learned the sequence, may commit an uncharacteristic error during the final recall. In summary, learning in the Hebb Digits task can either be statistically demonstrated by examining the trend in recall performance across the entire task or by selectively examining recall performance on the last presentation of the repeating series.

Theoretical Accounts of Hebb Digit Learning

Hebb (1961) originally accounted for performance in his repeating digits task as indicative of the development of a long-term representation of the repeating sequence. The repeating sequence was learned and could be recalled more accurately than the novel sequences presented on the intervening trials. The mechanism of learning was considered to be the continued exposure to the repeating sequence on every third trial. In the present section, we examine what has been learned about the Hebb repetition effect since Hebb's original work. In particular, we review the factors that contribute to learning in the Hebb Digits task, the factors that impede learning in the Hebb Digits task and the mode, implicit or explicit, by which learning occurs.

Learning of the serially ordered information in the Hebb Digits task appears to be based on the same principles as some of the models of short-term memory (Estes, 1972; Lee & Estes, 1977, 1981; Murdock, 1982, 1983; Shiffrin & Cook, 1978). Specifically, rehearsal of the repeating sequence during the course of the Hebb Digits task has been theorized to contribute to learning because at each repetition less information is required to represent the sequence as it acquires a more hierarchical trace in long-term memory (Nelson, 1971). This rehearsal could occur at two points in processing: during presentation of the digits and during production of the response.

As a result, both stimulus processes related to digit organization at input, and response processes related to digit organization at output, might be involved in transferring the repeating sequence from a short-term trace to a long-term structure.

Perceptual processes. Research examining perceptual processing in the Hebb Digits task has shown that temporal inconsistencies in the presentation of the repeating digits (e.g., 791 presented as "seventy-nine, one" on one trial and then, "seven, ninety-one" on a subsequent trial) (Bower & Winzenz, 1969) or altering the first few elements of the repeating string (Bower & Winzenz, 1969; Schwartz and Bryden, 1971) disrupt learning of the repeated sequence. It has also been found that learning of the repeated sequence is disrupted when the novel sequences contain digits in similar positions to the repeated sequence (Melton, 1964). However, researchers testing a positional model of Hebb Digits learning, in which it is theorized that items are coded in terms of exact serial position, have found that recall performance fails to improve when transferred to a sequence that retains half of the items in the identical positions as in the repeating sequence (Cumming, et al., 2003). These findings suggest that Hebb Digits learning is not based on the encoding of positional information. Moreover, learning of the repeated sequence does not result when items are separated from the context of the inter-item associations that have been previously formed. In other words, the representation of the string of digits in long-term memory is based on the particular chunks that have been formed among the items rather than the specific position of the items within the sequence.

In order to account for Hebb Digits learning, Bower and Winzenz (1969; p. 1) proposed the reallocation hypothesis whereby "alteration of the group structure of the same underlying digit string severely degraded memorial recognition of its repetition and that the normal improvement in immediate recall with repetition was annihilated by changing groupings at each presentation …group structure affects perceptual coding which determines "where" the trace of the event is stored." Deviations from this temporal ordering were hypothesized to interfere with recognition of the repeated sequence and thereby, alter the metaphorical location in memory where the sequence was stored. In Bower and Winzenz's view, learning of the repeated sequence resulted from reactivation of the sequence information through a process of reaccessing the location in memory where the sequence was stored. Interestingly, this reactivation of the repeating sequence must occur within a limited time frame; Melton (1963) found that learning of the repeated sequence in the Hebb Digits task did not occur when more than 5 intervening lists are presented between repetitions.

Bower and Winzenz's work is in agreement with theories of short-term memory in that the learning of the repeated sequence in the Hebb Digits task is an all-or-none process (Estes, 1972; Lee & Estes, 1977, 1981; Murdock, 1982, 1983; Shiffrin & Cook, 1978). Specifically, the all-or-none view assumes that if an item is forgotten, then there is no partial information about this item that is transferred from short-term to long-term memory. In other words, the only information that can be transferred from short-term to long-term memory is that which is remembered or learned. Nelson's (1971) work suggests that Hebb Digits learning is based on the gradual strengthening of remembered items into hierarchical structures or chunks. Thus, the organization of the items into consistent chunks through perceptual processes facilitates the strengthening of the memory trace for the remembered items.

Response processes. In memory tasks, the act of responding often serves as an additional rehearsal of the memorized information. Learning in the Hebb Digits task has also been shown to be mediated by response processes. Participants who are permitted opportunities to make complete overt responses to the repeating digit sequence are able to learn this sequence whereas those who are only permitted incomplete overt responses do not exhibit such learning (Cohen & Johansson, 1967). Moreover, active responding to the reoccurring sequence of digits has been considered to provide greater opportunities to develop elaborative associations among the digits compared to simply passive exposure (Cunningham, Healy & Williams, 1984). Thus, it appears that learning in the Hebb Digits task depends on two factors: perceptual processes to consistently encode the repeating digits, and active response processes to provide elaborative rehearsal of these digits.

Learning without awareness

It has been theorized that serially ordered information can be acquired with some mixture of conscious and non-conscious processes (Willingham & Goedert-Eschmann, 1999) although this has been the subject of much debate (e.g., Perruchet & Amorim, 1992; Shanks & Johnstone, 1998; Shanks & St. John, 1994; Stadler & Roediger, 1998; St. John & Shanks, 1997). When the knowledge acquired during learning is consciously available to the learner, learning is said to occur explicitly. In other words, the learner, after completing the task, is cognizant of having learned and can accurately describe what was learned during the task. Conversely, implicitly learned information cannot be consciously expressed by the learner and subsequent to task performance, the learner is not cognizant of having learned anything and is not able to report on exactly what was learned during the task. In the following sections, we will present the findings from different paradigms which have demonstrated implicit learning for serially ordered information.

Learning and awareness in the serial reaction time task. In a typical implicit learning task, such as the serial reaction time task (SRTT) (Lewicki, Czyzewska, & Hoffman,,1987; Nissen & Bullemer, 1987; for a review, see Clegg, DiGirolamo, & Keele, 1998), participants are asked to press a key that corresponds to the spatial location of a stimulus that appears on a computer monitor. Unbeknownst to participants, the locations at which the stimuli appear occur in a repeating pattern during a portion of the task. As a result, the reaction times (RTs) for keypresses will progressively speed up with increased exposure to the repeating pattern and will slow up with exposure to a different pattern. Faster responses to the repeating pattern of stimuli are taken as evidence that participants have learned the repeating pattern and can anticipate the spatial location where the stimulus will appear. However, as noted above, some participants are generally not able to verbalize what they have learned during the task, (Curran & Keele, 1993; Willingham, Nissen, & Bullemer, 1989), nor are they able to demonstrate sequence knowledge in a prediction task which requires indicating the next element in the sequence subsequent to being presented with one of the items (Nissen & Bullemer, 1987; Stadler, 1989). Thus, for these unaware participants, the SRTT is characterized by the acquisition of knowledge that exerts an influence on task performance, but without the availability of this knowledge to conscious awareness.

Learning and awareness in the artificial grammar task. Another type of task that is often used to demonstrate implicit learning is the artificial grammar (AG) task (Reber, 1967, 1989). In this task, participants are required to memorize strings of letters that either conform to the rules of a finite-state grammar or are arranged in random patterns. During this task, participants are provided with feedback as to the accuracy of their responses. The results indicate that those exposed to the rule-governed strings become better at memorizing these strings than the participants exposed to the random strings; this pattern of results is taken as evidence that learning is occurring. Later, when exposed to novel strings that either conform or do not conform to the rules, the participants trained on the finite-state grammar exhibit recognition rates ranging from 60-80% suggesting that they learned the finite-state grammar. However, these same participants are unable to report the rules that they are using to classify the letter strings. As a result, the AG task is considered to be an implicit learning task (Seger, 1994).

Learning and awareness in the Hebb Digits task. One of the early notions associated with performance in the Hebb Digits task was that performance in the task could occur in the absence of conscious awareness. This was first reported by Hebb (1961) who noticed that 15 of his 40 participants were unaware of the repeated digit string. Although Hebb reported a trend for learning the repeated digit string, he did not provide any data as to whether his unaware participants learned the repeated digit string. In later work, Baddeley and Warrington (1970) demonstrated that amnesic participants, who are incapable of storing new information in long-term memory, learned the repeated sequence significantly better than the random digit strings in the

Hebb Digits task. However, others using digit strings exceeding amnesiacs' digit span found no learning for the repeated sequence (Charness, Milberg, & Alexander, 1988; Milberg, et al., 1988), suggesting that digit span may be a factor influencing Hebb Digits learning even in participants who are unaware of the repeating digit sequence. Although performance results are mixed with amnesiac participants, McKelvie (1987) revealed that learning in the Hebb Digits task did not significantly differ across groups of normal participants classified as aware or unaware on the basis of questionnaire results and recall accuracy of the repeating sequence. The Hebb Digits task, therefore, has come to be identified as a form of implicit learning (Seger, 1994). There are, however, ongoing debates about whether implicit knowledge differs from explicit knowledge, and if so, how methodologically it should be assessed (e.g., Perruchet & Amorim, 1992; Shanks & Johnstone, 1998; Shanks & St. John, 1994; Stadler & Roediger, 1998; St. John & Shanks, 1997).

Despite being classified as an implicit learning task, the Hebb Digit task has several notable differences compared to other implicit learning tasks such as the SRTT and the AG task. First, learning occurs at a faster rate in the Hebb Digits task (e.g., 24 trials) and with less overall exposure to the repeating elements compared to the SRTT (e.g., several hundred trials) and AG tasks (e.g., > 50 trials depending on the rate of learning). Second, participants in the Hebb Digits task are explicitly instructed to learn the complete digit sequences, whereas such explicit instructions are absent from the SRTT and AG tasks. Third, performance feedback is generally not provided in the Hebb Digits task, whereas such feedback is a common component of SRTT tasks. Finally, in the Hebb Digits task the repeating digit sequence and the non-repeated digit sequences are intermixed. Conversely, the repeating information in SRTT and AG tasks is generally presented continuously throughout the task. However, Stadler (1993) integrated characteristics of the Hebb Digits task with the SRTT and found that implicit learning still occurred when the repeating and random elements were intermixed.

In modern work on implicit learning, the Hebb Digits task has fallen into disuse possibly due to two factors that make it problematic for studying learning in the absence of conscious awareness: 1) too few participants are unaware of the repeated information in the Hebb Digits task (about 20%) compared to other implicit learning tasks such as the SRTT and AG tasks, 2) there are a number of different techniques for scoring the Hebb Digits task whereas the scoring of performance in SRTT and AG tasks is fairly straightforward. Despite these difficulties, the Hebb Digits task is unique among implicit learning tasks in that it permits the study of implicit and explicit learning in a situation where performance is based on working memory processes.

Individual differences in Hebb Digits learning

Evidence that Hebb Digits learning can be potentially implicit in nature is an idea that appears to be at odds with Bower and Winzenz's (1969) reallocation hypothesis which attributes increased performance on the repeated sequence to recognition of the repetition. As mentioned previously, Bower and Winzenz attributed learning of the repeated sequence to the storage of this sequence in the same metaphorical memory location each time it is encountered. Reactivation of the reoccurring sequence on repeated trials both strengthens the memory trace for the repeated sequence and also mediates identification of it. Although McKelvie (1987) found equivalent learning of the repeated sequence for the aware and unaware participants, McKelvie's work, which represents the only empirical evidence for implicit learning in the Hebb Digits task among normal participants, may be challenged on the basis that participants differ in terms of preparedness for performing in the task. Specifically, McKelvie notes a significant difference in performance between the aware and unaware participants on the first block of trials such that the unaware participants demonstrate great variability in recall. Since McKelvie did not provide any practice trials prior to beginning the task, it may be the case that participants who are labeled as unaware have difficulty initially adapting to the task. Moreover, if Block 1 of McKelvie's experiment is considered to be a practice block, then the corrected scores of the unaware participants throughout the rest of the experiment do not demonstrate learning of the repeated sequence. Such a pattern of results would then be consistent with Bower and Winzenz's (1969) reallocation hypothesis in that the unaware participants were not able to recognize the repeating sequence and thus, develop a strong memory trace for this sequence with repeated activation.

The variable performance of the unaware participants on McKelvie's first block of trials points to another issue with regard to Hebb Digits performance, namely digit span. Participants who have a limited digit span may not be able to form the elaborative associations among sequence elements to strengthen the memory trace for the repeating sequence with each exposure. Evidence that digit span may mediate performance on the Hebb Digits task is suggested by the performance dissociation between amnesiac participants who could learn the repeated sequence under low digit span conditions (Baddeley & Warrington, 1970), but not when digit span was exceeded (Charness, Milberg, & Alexander, 1988; Milberg, et al., 1988). We will return to this issue of digit span and awareness in the Hebb Digits task in Chapter Three.

In summary, the Hebb Digits task is a simple yet powerful tool that can be used to study the long-term learning of serially ordered information. Specifically, the Hebb Digits task allows investigators to examine the transfer of serially ordered information from a transient state to a longer lasting representation in a relatively short 24-trial procedure. Based on modern research into the mechanisms responsible for learning in the Hebb Digits task, it appears that researchers still do not adequately understand exactly what is responsible for how the serially ordered information is organized in memory. The format of the Hebb Digits task has two phases: a perceptual phase during which participants are presented with the digits and a motor phase during which participants respond. If we are to accept the models of short-term memory which theorize that serial learning is based on an associative chunking process, then one of the critical issues to understand in Hebb Digits learning is which of the phases of the task, perceptual or motor, is primarily responsible for the associative learning that occurs with repetition. In other words, what type of associative information is being transferred from short-term to long-term memory, perceptual associations or motor associations. The understanding of the dialogue between the perceptual and motor phases of the Hebb Digits task will be an important step towards a greater understanding of how serially-ordered information is represented in long-term memory.

Research has also demonstrated that the transfer of serially-ordered information from short-term to long-term memory in the Hebb Digits task can occur with and without conscious awareness. Although the possibility that Hebb Digits learning can be implicit is at odds with Bower and Winzenz's (1969) reallocation hypothesis, it may be more compatible with a comprehensive theory of memory as a distributed system (Lewandowsky & Murdock, 1989; Murdock, 1982, 1983), in which the storage of information is not localized, but in a pooled form, and thus, capable of being reactivated through many possible routes, some conscious and some non-conscious. However, the lack of a formal theoretical explanation for how implicit learning could occur in the Hebb Digits task coupled with questionable empirical support for implicit learning in this paradigm points to an unresolved issue: Is the Hebb Digits task an implicit learning paradigm? This issue will be investigated as part of a series of proposed experiments in Chapter Three.

CHAPTER TWO

STIMULUS AND RESPONSE CHUNKING IN THE HEBB DIGITS TASK[1]

Based on the review of the Hebb Digits task presented in Chapter One, learning in the Hebb Digits task is a process by which a hierarchical trace of the repeating sequence develops through repeated exposure to it during the course of the experiment. Such learning can occur through either stimulus or response processes. It is, therefore, important to understand which of these processes, the presentation of the stimuli or the execution of the responses, is more dominant in Hebb Digits learning. The format of the Hebb Digits task not only requires the use of working memory processes, but also enables the separate investigation of the effects of perceptual and motor chunking on serial learning performance. In Chapter Two, we present the findings from a series of experiments in which the organization of the digits either at presentation or response was systematically varied in order to assess which processes, perceptual or motor, are more in important in Hebb Digits learning.

As mentioned in Chapter One, the Hebb Digits task has come to be identified as a form of implicit learning (Baddeley & Warrington, 1970; McKelvie, 1987; Seger,

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[1] The material in Chapter Two is reprinted from a forthcoming article: O'Shea, G. & Clegg, B. A. (in press). Stimulus and response chunking in the Hebb Digits task. Psychological Research. This article is reproduced here with kind permission of Springer Science and Business Media.

1994; Stadler, 1993). There are, however, ongoing debates about whether implicit knowledge differs from explicit knowledge, and if so, how methodologically it should be assessed (e.g., Perruchet & Amorim, 1992; Shanks & Johnstone, 1998; Shanks & St. John, 1994; Stadler & Roediger, 1998; St. John & Shanks, 1997). Given this uncertainty about the concept of "implicit", in the current study we followed the lead of Koch & Hoffman (2000) in another form of implicit learning, and most of the previous work with the Hebb Digits task (e.g., Bower & Winzenz, 1969; Cohen & Johansson, 1967; Cunningham, Healy, & Williams, 1984; Hebb, 1961; Nelson, 1971; Schwartz & Bryden, 1971), and avoid focusing on any specific distinctions regarding the nature of conscious awareness or its role in performance. At this point, one central issue, which does not require tests of implicit versus explicit knowledge, is simply to develop an improved understanding of the underlying mechanisms mediating this type of incidental learning task.

Based on the review of the Hebb Digits task presented in Chapter One, it appears that learning in this task relates to two factors: perceptual processes to encode the digits consistently at each occurrence of the repeating series, and active response processes to provide elaborative rehearsal of the repeating sequence. Thus, one important question concerns the extent to which learning in the Hebb Digits task arises from the establishment of long-term traces of perceptual versus motor information.

Research using a digit entry task, in which participants are required to type back digits that appear on a computer screen using a keypad, has offered evidence for separate long-term memory traces for the perceptual and motor aspects of performance (Fendrich, Healy, & Bourne, 1991). Specifically, Fendrich and colleagues found that after extensive training on the digit entry task, participants demonstrated successful transfer of training to tasks that separately retained either the same perceptual sequences of digits or the same motor pattern of keypresses. However, unlike the format of the Hebb Digits task, Fendrich et al.'s procedure required typing 3 digit sequences that were present on a computer screen rather than retrieving the digit sequences from memory. Thus, it remains to be determined how performance in a task such as the Hebb Digits task, which is more reliant on the retrieval of information from memory, would relate to functionally independent perceptual and motor traces.

Chunking and serial learning

One notion of the basis of serial learning is that it arises from the establishment of chunks of information within memory. More specifically, serial learning can be characterized as a conversion of larger units of information into smaller units, through chunking, in order to bypass limitations in short-term memory capacity (Gobet, Lane, Croker, Cheng, Jones, Oliver, & Pine, 2001; Johnson, 1970; Miller, 1956). Chunking has been considered a naturally occurring mechanism, independent of conscious intention (Servan-Schreiber & Anderson, 1990); and it spontaneously emerges even in tasks where the information to be learned is not specifically structured (Chase & Ericsson, 1981; Johnson, 1970; Tulving, 1962). When stimuli are organized according to some imposed structure, it has been found that the organization of responses then mimics the structure of the stimuli (Bower & Springston, 1970; McLean & Gregg, 1967). Similarly, experimenter-imposed response structures can also produce motor chunks in a variety of conditions ranging from explicit (Povel & Collard, 1982; Restle & Burnside, 1972) to implicit learning (Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993; Keele and Jennings, 1992; Koch & Hoffman, 2000; Nissen & Bullemer, 1987; Stadler, 1989, 1993).

One account of the improved performance for the repeating series in the Hebb Digits task is that a chunking mechanism restructures stimulus and/or response information into a more hierarchical trace, and hence more information can be acquired on those trials. Indeed Lewandowsky and Murdock (1989) showed that performance in the Hebb Digits task could be successfully simulated with a computer model based on the strengthening of pairwise associations into higher order units through chunking.

At present, no study has systematically evaluated how the separate stimulus and response processes interact in the Hebb Digits task. One study, by Winzenz and Bower (1970), examined learning when the repeated digits were organized in groupings that were either matched or mismatched at presentation and response. Specifically, Winzenz and Bower (1970, p. 53) trained participants to vocally respond to digit sequences arranged in different groupings on each trial in chunks of 3, using a shadowing technique whereby they "mouthed the numerical name of each group" during presentation and then after the digits were read, then transcribed their sequence "by writing the individual digits...on a recall sheet." In other words, participants consciously recoded the experimenter-imposed groupings into chunks of 3 during presentation. Winzenz and Bower's results indicated that learning was strongest when the structure of the experimenter and participant chunks was matched, and weakest when the experimenter groupings of the repeated digits varied from trial to trial, but participants' chunks remained consistent.

While Winzenz and Bower's results suggest that mismatched stimulus and response chunks decreased learning, the interpretability of their results are complicated by their trial procedure. As described above, participants were required to say groups of three digits at a time while the entire digit string was being read. Thus, two potential sources for decreased learning were present. On the one hand, there was a mismatch between the information presented by the experimenter and the format of the response series required. However, on the other hand, there was also a mismatch between the information presented by the experimenter and the recoded version of the series being immediately repeated by the participants. The production by participants of recoded strings of digits concurrently with the presentation of the original items has the potential to create interference between the two forms of information, with neither version being optimally encoded. Despite their trial procedure, Winzenz and Bower (1970), nevertheless, demonstrated that learning still occurred when an inconsistently organized stimulus input was recoded into consistent response chunks.

In a different form of implicit learning, the serial reaction task (SRT) (e.g., Nissen & Bullemer, 1987; for a review see Clegg, DiGirolamo & Keele, 1998), when the perceptual and motor aspects are separately established, the relational structure of the keystroke sequence more strongly contributes to sequence learning than the relational structure of the stimuli (Koch & Hoffman, 2000). In contrast to the SRT, the format of the Hebb Digits task is far more reliant on working memory processes in retaining the sequence of digits prior to responding. For example, the Hebb Digits task includes relatively few motor responses (in comparison to the approximately 50 to 100 cycles through a sequence found in SRT learning, Hebb Digits responding typically features only 8 cycles through the repeating sequence). As a result, in the Hebb Digits task greater effort is likely to be expended on rehearsing the digits according to the perceptual input rather than through responding.

The present study revisited Winzenz and Bower's (1970) work on the interaction of stimulus and response chunks. However, we used a methodology that enabled manipulations of the stimulus and response phases of the Hebb Digits task, while avoiding the complications present in Winzenz and Bower's shadowing technique. In the first experiment, learning under four conditions was examined: a non-chunked baseline condition where neither the stimuli nor the responses were chunked; a response-chunked condition which required the execution of responses in chunks of three to individually presented, non-chunked stimuli; a stimuli-chunked condition where responses were executed in a non-structured format to stimuli presented in chunks of three; and finally, an all-chunked condition where both stimuli and responses were matched in chunks of three. Based on the dominance of perceptual processes for organizing responding in the Hebb Digits task, we predict that the contribution of motor chunking to learning in the response-chunked and all-chunked conditions would be negligible to the learning in the non-chunked and stimuli-chunked conditions.

EXPERIMENT 1

The initial experiment was designed to examine the differential contributions of stimulus and response chunking on learning in the Hebb Digits paradigm. As discussed above, the format of the Hebb Digits task permits separate manipulations of the organization of stimuli and responses such that the effect of chunking on performance can be evaluated. Our procedure altered Hebb's (1961) original task from a verbal presentation and vocal responses to visual presentation of stimuli on a computer and responses typed on a keyboard. This methodology offered the potential for additional control over the presentation and response formats, as well as allowing for precise timings.

METHOD

Participants

Seventy-two participants were recruited from students obtaining optional partial credits for a General Psychology class. All participants gave informed consent. There was no overlap of participants across any of the experiments.

Stimuli and Apparatus

All of the experiments were run on an Apple MacIntosh computer using PsyScope software (Cohen, MacWhinney, Flatt & Provost, 1993). Digits were presented in 12 point Chicago font in the center of the screen. Responses were made with the participant's dominant hand using the number keys from the top row of a standard keyboard.

Procedure

Participants were presented a nine-item series of digits comprised of 1 to 9 in varying order, without repetition of individual digits (e.g., 817394652). Each trial began with an asterisk that served as a fixation symbol, followed 500 ms later by the first digit(s) of the sequence. Two presentation formats were used. In the non-chunked presentation conditions, items from the sequence were presented individually at the rate of 1 digit per sec. until all nine items had been viewed. In the chunked presentation, the digits for each trial were viewed in groups of three based on previous research identifying such chunks as facilitating optimal recall performance (Wickelgren, 1967). Thus a participant would initially view three digits for 3 sec. (e.g. "817"), followed by the next three digits for 3 sec. ("394") and finally the last three digits for 3 sec. ("652"). Note that this equates the amount of presentation time across the conditions, with all groups studying a total of nine digits for 9 sec.

Participants were instructed to memorize the entire sequence of digits. Immediately following the last digit(s), participants were presented with a prompt ("Enter:"). Participants then typed their memorized series (that appeared on the screen) in one of two formats. In the non-chunked condition, participants entered a single string comprised of as many of the nine items as they could recall. Each trial ended when participants pressed the Return key to indicate when typing of the digit series was complete. In the chunked condition, responses were executed according to a fixed chunking structure of three groups of three items (rather than a single set of nine responses).

Participants in all conditions were encouraged to recall or guess the sequence of digits in its correct order. However, leaving a blank for a forgotten digit was also acceptable. All trials were terminated by pressing the Return key. In the chunked response condition, participants, unable to recall a digit, could either guess or leave a blank by terminating the chunk with a press of the Return key. After the key press to indicate the end of digit series entry, there was a 2000 ms inter-trial interval with the screen blank. A fixation point then appeared to signal the start of the next trial. Participants were not provided with any feedback regarding performance, were encouraged to balance the speed and accuracy of their responses, and were instructed to refrain from backspacing. Prior to beginning the 24 experimental trials, all participants in each of the conditions received ten practice trials to familiarize them with the procedure.

Design

Beginning with the third experimental trial, the same 9-digit sequence (726519384) was repeatedly presented on every third trial ("Repeated"). Participants were not informed of the repetition and thus learning was incidental. The digit sequences on the remaining trials were novel, random series of digits ("New") and were unrelated to each other and the repeating sequence. Learning was assessed by comparing performance on the repeating series to performance on the new sequences encountered on the other trials.

Participants were randomly assigned to one of four groups (with 18 subjects per group): neither presentation nor response execution chunked ("No Chunking"), stimulus presentation chunked but responses not chunked ("Stimulus Chunked"), response execution chunked but stimulus presentation not chunked ("Response Chunked"), and both stimulus presentation and response execution chunked ("All Chunked").

Measures

There are multiple ways to assess performance in the Hebb Digits task (for a review see McKelvie, 1987). McKelvie advocated a four step scoring procedure to quantify the level of recall for each series, scoring forwards through the sequence, scoring backwards through the sequence, scoring for correct pairwise transitions, and scoring for correct serial position. For each participant the mean McKelvie score for trials on the series repetitions (trials 6, 9, 12, 15, 18, 21, & 24) and for the surrounding new sequence trials (trials 5, 7, 8, 10, 11, 13, 14, 16, 17, 19, 20, 22, & 23) were calculated.

However, in these experiments the liberal nature of the McKelvie scoring procedure tended to produce near ceiling-level performance when digits were presented in chunks. For example, in trial 24, the final repeating sequence was recalled with a mean score of 8.8 (out of 9) in the All Chunked group, and with a mean score of 8.3 in the stimulus chunked group. As can be readily seen, this would tend to leave very little scope to detect variations in performance using the McKelvie scores.

Since such high recall scores had the potential to mask effects, a more conservative measure was therefore employed in the analyses reported below[2]. One

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[2] In all of the experiments the same general pattern of results was found using both McKelvie's (1987) scoring method and analyses based on perfectly recalled trials. However, the analyses using McKelvie's method did not always reach statistical significance.

performance gauge used by Hebb (1961) in his original experiment was to compare trials with perfect versus imperfect recall. In adopting a similar index, data in these experiments were analyzed in terms of the proportion of trials in which the entire series of 9 items was completely and correctly recalled. Again the separate scores were generated for the reoccurring series (trials 6, 9, 12, 15, 18, 21, & 24) and for the surrounding new sequence trials (trials 5, 7, 8, 10, 11, 13, 14, 16, 17, 19, 20, 22, & 23).

To confirm that the results observed were not a product of the relatively conservative measure, analyses were also conducted using the number of consecutive correct items (starting from the first item of the presented series) as the dependent variable. In adopting these additional analyses, we reasoned that this would be sensitive to the inter-item associations that comprise the formation of chunks and would therefore, be sensitive to performance in the Hebb Digits task.

RESULTS

In order to examine whether chunking provided benefits for learning, a mixed ANOVA of digit series type ("Repeated", "New") by chunking condition ("No Chunking", "Stimulus Chunked", "Response Chunked", "All Chunked") was conducted. A main effect of series type ($\underline{F}(1,68)=64.30$, $\underline{p}<.05$, MSE =.032, partial $\eta^2 = .49$), with greater recall for repeated series compared to the novel series, showed learning had occurred (mean proportion of trials with all nine items correct: Repeated = .40, New = .17). The main effect of chunking condition ($\underline{F}(3,68)=16.56$, $\underline{p}<.05$, MSE =.075, partial $\eta^2 = .42$) was congruent with the well established advantage of chunked information for the short-term memorization of digits required on each trial in this paradigm (proportion with all nine items correct: No Chunking = .06, Response Chunked =.20, Stimulus Chunked = .42, All Chunked = .46).

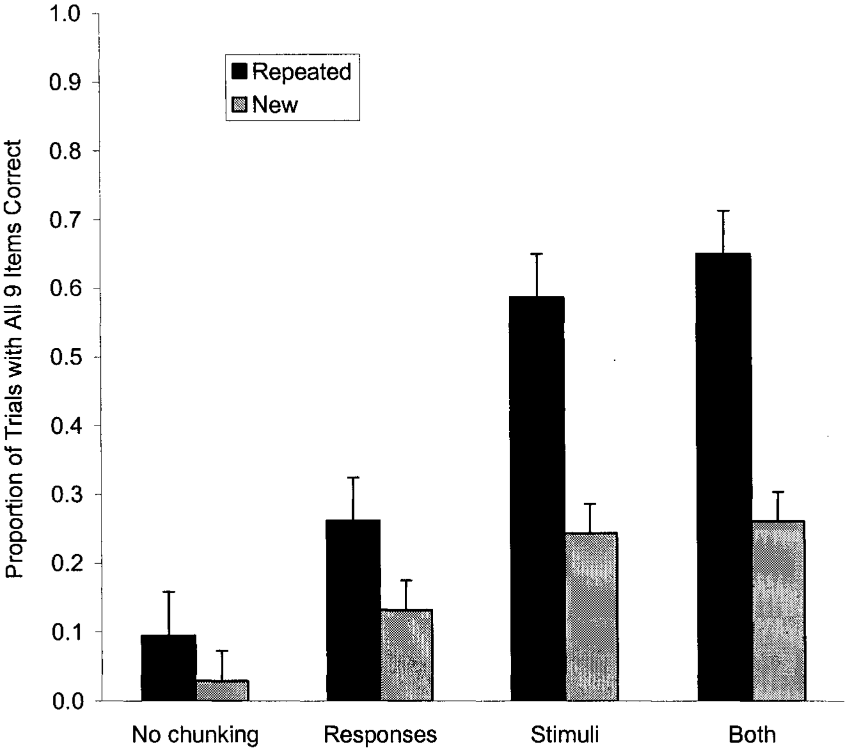

Figure 2.1 Recall performance for random ("new") versus reoccurring ("repeated") series of digits as a function of chunked condition. The four conditions, based on the structure of the stimuli and responses, are as follows: No Chunking (stimuli presented individually/responses unstructured), Responses (stimuli presented individually/responses executed in chunks of three), Stimuli (stimuli presented in chunks of three/responses unstructured), and Both (stimuli presented in chunks of three/responses executed in chunks of three). (Error bars indicate standard error).

Crucially for the assessment of whether learning gained additional benefits from chunking, a significant interaction between series type and chunking condition was observed ($F(3,68)=7.53$, $p<.05$, partial $\eta^2 = .25$; see Figure 2.1). Follow-up analyses were then used to compare each chunking condition individually to the baseline (No Chunking condition).

For the comparison of just the All Chunked to No Chunking groups, a significant interaction between series type and chunking condition was found ($F(1,34)=20.47$, $p<.05$, MSE =.023, partial $\eta^2 = .38$). In the comparison of the Stimulus Chunked group to the No Chunking group, an interaction was again present ($F(1,34)=12.90$, $p<.05$, MSE =.027, partial $\eta^2 = .28$).For the comparison of just the All Chunked to No Chunking groups, a significant interaction between series type and chunking condition was found ($F(1,34)=20.47$, $p<.05$, MSE =.023, partial $\eta^2 = .38$). In the comparison of the Stimulus Chunked group to the No Chunking group, an interaction was again present ($F(1,34)=12.90$, $p<.05$, MSE =.027, partial $\eta^2 = .28$). For the comparison of the Response Chunked group to the No Chunking group, no statistically significant interaction was observed ($F(1,34)<1$, MSE =.019, partial $\eta^2 = .03$). Therefore, learning does not appear to significantly benefit solely from the execution of responses in chunks.

One issue raised by these analyses was whether the match in chunking between stimuli and responses provided additional benefits beyond those found for stimulus chunking alone. A comparison of the All Chunked group to the Stimulus Chunked group, produced no hint of a significant interaction ($F(1,34)<1$, MSE =.042, partial

$\eta^2 = .01$). Finally, as outlined above, the same analyses were conducted using the number of consecutive correct items as the dependent variable. These analyses replicated all of the above findings, with a main effect of series type ($F(1,68)=53.63$, $p<.05$, MSE =0.63, partial $\eta^2 = .56$; mean consecutive items correct: Repeated = 6.8, New = 5.5); a main effect of chunking condition ($F(3,68)=16.35$, $p<.05$, MSE =3.11, partial $\eta^2 = .42$; mean No Chunking = 4.5, Response Chunked =6.0, Stimulus Chunked = 7.0, All Chunked = 7.1); and a significant interaction between series type and chunking condition ($F(3,68)=3.30$, $p<.05$, partial $\eta^2 = .13$). Moreover, exactly the same pattern of findings emerged from the follow-up test: with significant interactions between series type and chunking condition found for the All Chunked versus the No Chunking groups ($F(1,34)=12.03$, $p<.05$, MSE =0.43, partial $\eta^2 = .26$) and the Stimulus Chunked group versus the No Chunking group ($F(1,34)=5.09$, $p<.05$, MSE =0.71, partial $\eta^2 = .13$) and no significant interaction for the Response Chunked group versus the No Chunking group ($F(1,34)=1.29$, $p>.05$, MSE =0.58, partial $\eta^2 = .04$). A comparison of the All Chunked group to the Stimulus Chunked group, once again produced no hint of a significant interaction ($F(1,34)<1$, MSE =0.67, partial $\eta^2 = .01$). These results therefore suggest that the previous findings were not simply an artifact of the conservative scoring system adopted for recall.

DISCUSSION

The present findings supported our hypothesis that learning in the Hebb Digits task is primarily a function of perceptual processes. Indeed, the Response Chunked condition did not produce significant gains in learning of the repeating series compared to the No Chunking condition. It is possible that some benefits for learning from response chunking did occur, and that a lack of power underlies the non-significant result. However, the effect sizes tend to suggest any advantages would be minor. The negligible contribution of response processes to learning performance in the Hebb Digits task is further illustrated by the failure of the All Chunked condition to produce significant gains in learning compared to the Stimulus Chunked condition.

Several researchers (e.g., Melton, 1963; Nelson, 1971) have been interested in the Hebb Digits paradigm as a means of studying the transfer of information from short-term memory to long-term memory. The findings of this experiment support the idea that chunking enhances such a process by possibly freeing up more resources for greater efficiency of encoding and response production processes. However, the failure to obtain significantly greater learning for response chunking suggests that what people are storing in long-term memory are sequences of perceptual events rather than sequences of actions. The failure of response chunking to significantly improve learning also suggests, contrary to Cunningham et al.'s (1984) theory, that the organization of responses into consistent chunks does not constitute a more active form of rehearsal compared to responding in an unstructured format where, perhaps, item-to-item associations are strengthened by the greater consistency between the organization of stimuli and the organization of responses.

There is evidence that motor chunking benefits some very different forms of implicit learning (e.g., Cohen et al., 1990; Koch & Hoffman, 2000; Verwey & Dronkert, 1996); however, these results using the Hebb Digits task suggest that such structured responding does not significantly contribute to learning in this paradigm. While it is plausible that learning is entirely independent of the response properties, an alternative explanation may be offered for the failure of response-based chunking. Under the uniform rate of stimulus presentation (1 digit/sec), participants may spontaneously form their own consistent grouping of digits (either a single series or a set of chunks) that subsequently proves to be incongruent with the structure required for the Response Chunked condition. The mismatch between the stable structure developed at encoding and the different structure demanded during recall might interfere with learning by weakening item-to-item associations and effectively creating two weak traces of the repeating series. Under such conditions, more errors are likely to occur in recall from short-term memory. We return to this issue in the discussion of Experiment 3.

The failure to observe significant differences in learning performance between the All Chunked and Stimulus Chunked conditions may reflect the findings, discussed above, that stimulus-based chunking might tend to induce corresponding chunking of the responses (e.g., Bower & Springston, 1970; McLean & Gregg, 1967). In effect, with a free response structure participants may choose to emit their responses in the same clusters of 3 items present during encoding and therefore, the perceptual and motor chunks would be identical in the two conditions. Thus, the first experiment may not have isolated the effects of stimulus-based chunking; and the enhanced learning could have been entirely due to the match between the encoding structure and the recall structure. This issue formed the basis for Experiment 2.

EXPERIMENT 2

Experiment 2 was designed to test whether the encoding of uniformly presented stimuli, as well as stimuli presented in chunks, is susceptible to disruption by random responding. Forcing a mismatch between the codes developed at presentation and at recall would likely cause interference in converting between chunks and offers an assessment of whether stimulus chunks are resilient to being reorganized into different chunks during responding.

METHOD

Except where noted methodology for the following experiments matched that of Experiment 1.

Participants

Fifty-six participants were recruited from students obtaining credit for a General Psychology class.

Procedure

The procedure mirrored that used in Experiment 1 except for the following change: 1) Responses were executed according to a random chunking structure with groupings of varying sizes. Except for one trial in which all 9 responses were executed individually, all of the remaining groupings consisted of three sets, with a given set containing from one to five responses. The number of items in each response chunk was determined randomly. Participants entered a set of responses equivalent to the number of asterisks shown preceding the “enter” prompt on the computer screen, and pressed the Return key to indicate completion of entry for the chunk.

Design

Again, every third trial featured a repetition of an identical sequence of digits, with learning assessed by comparing the repeating sequence to the new sequences present on the other trials. However, random chunking of the repeated series meant that while the same order of nine digits was encountered, the grouping of items varied from trial to trial (i.e., the same chunk structure was never re-presented in the repeating series trials).

Participants were randomly assigned to one of two stimulus presentation conditions (as used in Experiment 1), either with individual presentation of the nine single digits each of 1 second ("No stimulus chunking") or with chunked presentation of three sets of three digits with each chunk viewed for 3 seconds ("Stimulus chunked").

RESULTS

A mixed ANOVA of digit series type ("Repeated", "New") by stimulus chunking condition ("No Stimulus Chunking", "Stimulus Chunked") was conducted. There was a significant main effect of chunking condition ($\underline{F}(1,54)=3.96$, $\underline{p}=.05$, MSE =.083, partial $\eta^2 = .07$); proportion with all nine correct: No Stimulus Chunking = .20, Stimulus Chunked =.31). The critical finding was a significant interaction between series type and chunking condition ($\underline{F}(1,54)=6.47$, $\underline{p}<.05$, partial $\eta^2 = .11$; see Figure 2.2). For the new series of digits, no statistically significant differences between stimulus formats was present ($\underline{F}(1,54)<1$, $\underline{p}>.05$, MSE =.027, partial $\eta^2 = .01$); however, for the repeating series an advantage for the chunked stimuli was found ($\underline{F}(1,54)=5.97$, $\underline{p}<.05$, MSE =.084, partial $\eta^2 = .10$). Therefore learning of the repeating series did benefit from consistent chunking of the stimuli.

A main effect of series type was also found ($\underline{F}(1,54)=32.08$, $\underline{p}<.05$, MSE =.028, partial $\eta^2 = .37$) indicating a greater recall for the repeated series compared to the novel series (proportion of trials with all nine items correct: Repeated = .34, New = .17). Since interpretation of main effects needs to be done in the context of the significant interaction reported above, an additional analysis of the No Stimulus Chunking group for repeated versus novel series was conducted. The results showed a significant advantage for the repeating series ($\underline{t}(27)=2.70$, $\underline{p}<.05$; repeated = .24, novel =.13). Thus, learning was found with random response structures imposed, even in the absence of stimulus chunking, and the significant interaction reflected enhanced learning with stimulus chunking.

Comparison of learning in Experiments 1 & 2

Although these analyses showed that learning could be based on stimulus characteristics alone, it remained possible that a consistent coding between stimulus and response structures produced superior learning. A comparison of performance in the stimulus chunked condition from this experiment with the stimulus chunked condition in the first experiment was therefore conducted. The point of this comparison was to assess whether learning would be significantly different in a stimulus chunked condition with a free response structure than in a stimulus chunked condition featuring a random response structure. The main effect of response format in this analysis was non-significant ($\underline{F}(1,44)=2.32$, $\underline{p}=.14$, MSE =.108, partial $\eta^2 =$

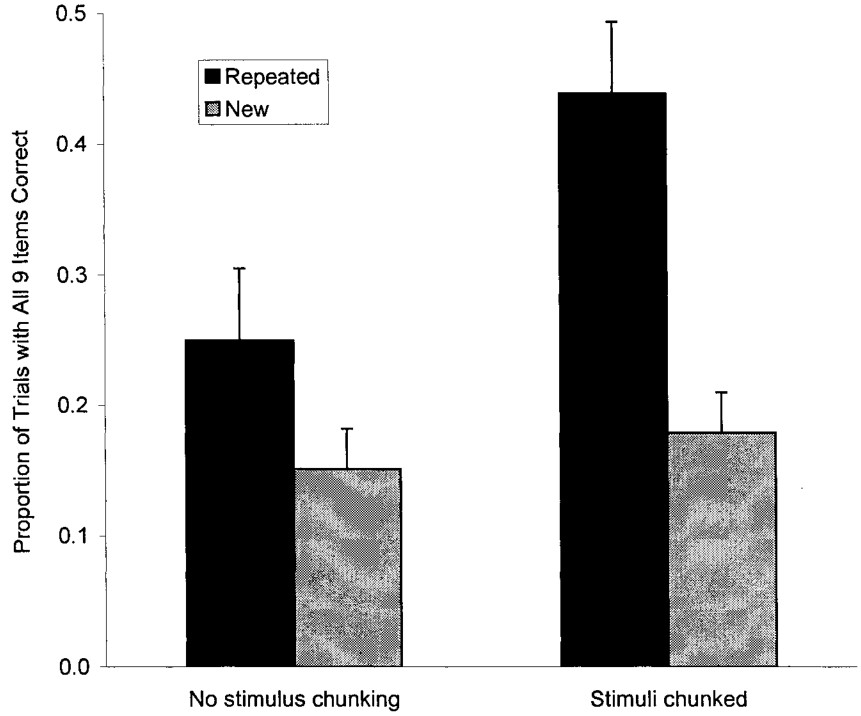

Figure 2.2 Recall performance for random ("new") versus reoccurring ("repeated") series of digits as a function of random responding with digits presented individually (No Stimulus Chunking) or in chunks of three (Stimuli Chunked). (Error bars indicate standard error).

.05); mean proportion of all 9 items correct with free response format in Experiment 1 = .42, mean with random response format in Experiment 2 = .31). Although not statistically significant, there was some hint that random response structure that mismatched the stimulus structure in Experiment 2 may have had some slight overall disruptive impact. Importantly for this analysis, no significant interaction between series type and response format was observed (F(1,44)<1, partial $\eta^2 = .02$). As the effect size shows, any impact of random response structure on learning with stimulus chunking was negligible. The enhanced learning for stimulus-based chunking was therefore not dependent on a corresponding response structure.

A comparison of the no stimulus chunking group in Experiment 2, in which responses were randomized, with the no chunking group from Experiment 1, that were free to develop any response structure, yielded a significant main effect of response format (F(1,44)=9.51, p<.05, MSE =.044, partial $\eta^2 = .18$; mean with free response format in Experiment 1 = .06, mean with random response format in Experiment 2 = .20). There was, however, no hint of an interaction between series type and response format (F(1,44)<1, partial $\eta^2 = .01$). The results of this comparison again suggest that random response structuring made no difference to learning of the repeating series. However, it is interesting to note that a general chunking strategy with responses did improve performance on each series, perhaps due to increased motivation to respond since the number of responses to be made was pre-specified, but the lack of consistency in this response structure apparently prevented it from benefiting learning of the repeating series.

DISCUSSION

Randomization of response structure failed to disrupt learning in both the No Stimulus Chunking and Stimulus Chunked conditions. Furthermore, an advantage for stimulus-based chunking was observed even when correspondence with response format did not match. These data suggest that stimulus characteristics appear to drive chunk formation in the Hebb Digits task and are resilient to conditions that prevent preparation of a specific sequence of responses in advance. One possibility is that the dominance of perceptual processes in organizing the input, prior to random responding, may reflect the reliance of the Hebb Digits task on working memory processes. Specifically, in the random response condition, participants must decompose the encoded sequence into smaller chunks in order to respond while simultaneously keeping a mental representation of the remaining information needed to complete the response.

The persistence of learning under conditions of random responding suggests that the encoding of consistently organized information, either presented at a rate of 1 digit or 3 digits/sec, facilitates the development of a sequence representation that is flexible enough to be decomposed into smaller chunks without impairing accuracy. Thus, the negligible effects of random responding on learning in the Hebb Digits task reflects the operation of stimulus processes in organizing the input into a flexible representation that can be reorganized to adapt to a partial response format.

While these initial experiments suggest that stimulus-based chunking effects dominate performance in the Hebb Digits task, they leave open the possibility that in the absence of coherent perceptual information, relationships between response-based information may then play some role in learning. Essentially, the question is whether response-based processes can feed back into the storage of information in order to develop an efficient method to organize learning.

EXPERIMENT 3

In the next experiment, the effect of response-based chunking under conditions that disrupted the formation of stimulus chunks during encoding was examined. Bower and Winzenz (1969) found that inconsistently organized stimuli disrupted serial learning, although as discussed above, subsequently they showed (Winzenz & Bower, 1970) that recoding could overcome this disruption. Under inconsistent organization, the repeated series is chunked differently at each presentation. Without the formation of a consistently rehearsed code, Bower and Winzenz (1969) suggested there was no strengthening of the repeated information over time that could contribute to incidental learning. However, under conditions featuring randomly presented stimuli, response-based chunking could provide a source for consistent grouping, and hence lead to the incidental learning of the repeated sequence. Thus, it was hypothesized that the disruption of any consistent pattern during encoding would induce greater reliance on the consistently executed response-based chunks.

METHOD

Participants

Fifty-nine participants were recruited from students obtaining credit for a General Psychology class.

Procedure

The procedure was the same as used in Experiment 1 with the following exceptions: Rather than presenting digits individually or in fixed chunk sizes of 3 items, each trial featured groups of differing configurations of the digits (following the same characteristics as the random response chunking in Experiment 2). The chunks again appeared on screen for a length of time equal in seconds to the number of digits in the set. For example, in a 5-3-1 chunk, a participant would initially view 5 digits for 5 sec (e.g. "81739"), followed by 3 digits for 3 sec ("465") and finally by 1 digit for 1 sec ("2").

Design

Again every third trial featured a repetition of an identical sequence of digits, with learning assessed by comparing the repeating sequence to the new sequences present on the other trials. However, random chunking of the repeated series meant that while the same order of nine digits was encountered, the grouping of items varied from trial to trial (i.e., the same chunk structure was never re-presented in the repeating series trials).

Participants were randomly assigned to one of two response conditions (as used in Experiment 1), either entering all nine digits in a single string ("No Response Chunking") or entering digits as three sets of three ("Response Chunked").

RESULTS

The results reflect the performance of 58 participants; one participant was dropped from analysis due to the unusually poor performance that resulted from not following instructions (mean number of items recalled per trial = .05 items out of 9).

A mixed ANOVA of digit series type ("Repeated", "New") by response chunking condition ("No Response Chunking", "Response Chunked") was conducted. The main effect of chunking condition ($\underline{F}(1,56)=1.83$, $\underline{p}>.05$, MSE =.065, partial $\eta^2 = .03$) was not statistically significant (proportion with all nine correct: No

Response Chunking = .21, Response Chunked =.27). A significant interaction between series type and chunking condition was observed (F(1,56)=6.08, $p<.05$, partial $\eta^2 = .10$; see Figure 2.3). For the new series of digits, no statistically

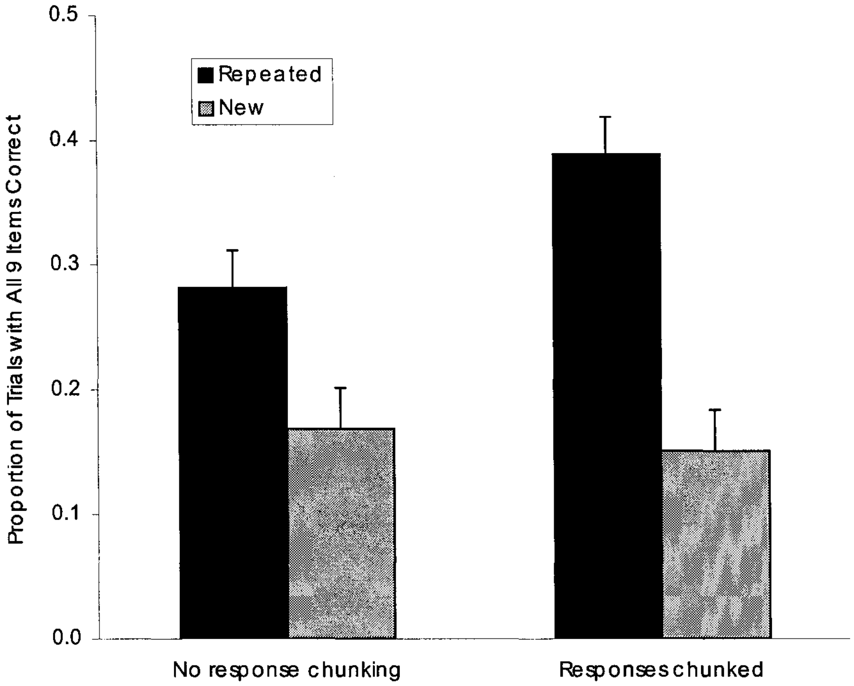

Figure 2.3 Recall performance for random ("new") versus reoccurring ("repeated") series of digits as a function of random stimulus presentation when responses are unstructured (No Response Chunking) or executed in chunks of three (Responses Chunked). (Error bars indicate standard error).

significant differences between the chunking conditions was observed (F(1,56)<1, $p>.05$, MSE =.018, partial $\eta^2 = .00$); however, for the repeating series a non-significant advantage for the chunked responses was found (F(1,56)=3.69, $p=.06$, MSE =.069, partial $\eta^2 = .06$). A main effect of series type was also present ($F(1,56)=36.21$, $p<.05$, MSE =.023, partial $\eta^2 = .39$), with greater recall for the repeated series compared to the novel series. This effect shows learning had occurred (proportion of trials with all nine items correct: Repeated = .32, New = .15). As in Experiment 2, the interpretation of the main effect of series type, therefore, needs to be done in the context of the significant interaction. A further analysis was carried out to assess learning in just the "No Response Chunking" group. The results showed a significant advantage for the repeating series ($t(27)=2.70$, $p<.05$; repeated = .25, novel =.13), and thus learning had occurred even in the group without chunking. The significant interaction of chunking conditions and series type apparently reflects enhanced learning with response chunks present rather than an absence of learning in the no response chunking conditions.

DISCUSSION

By demonstrating learning in the "No Chunking" condition, our results disagreed with Bower and Winzenz's (1969) classic findings. These data suggest learning of the repeating series with irregularly chunked presentation patterns can still occur. The divergence between these experimental results and those from previous research might be attributed to differences in experimental design. For example, Bower and Winzenz used a format in which stimuli were presented auditorily and responses were manually executed, while the current experiment used a visual/manual format. As Bower and Winzenz (1969; p.2) have indicated, the auditory condition "appears to afford the strongest control over S's groupings" since both pauses and rhythmical stress could exert effects on digit grouping. Bower and

Winzenz's study also differed from ours in their use of fewer trials (i.e., 12 as opposed to 24). As a result, this study permitted greater opportunity for learning to occur.

Although the results from Experiment 1 suggested that response chunking was insufficient to induce changes in serial learning for uniformly presented stimuli, these results imply that in the context of random stimulus presentation, consistent chunking of responses appeared to facilitate learning to a small extent. As discussed previously, one mechanism underlying an advantage for the response-based chunking of randomly organized stimuli would be the disruption of the development of a consistent encoding chunk. As a result, the encoding chunk is not rehearsed uniformly on each trial and there is less conflict when converting between chunks, as well as more reliance on the response-based chunk as a mechanism to organize the stimuli. Such data fit with the idea that incidental learning may be opportunistic, utilizing whatever forms of regularity exist to optimize learning.

A second plausible explanation is that consistent response chunking encourages participants to recode the data stream after presentation, and rehearse it in a consistent format. Such an account might suggest that consistent response chunking merely operates like the type of strategic reorganization that Winzenz and Bower (1970) trained their subjects to perform. While we cannot rule out such an explanation, it may seem somewhat unlikely that such a spontaneous strategy would emerge when digits are presented in random chunks but not when digits were presented as individual items (as in the Response Chunked condition in Experiment 1).

In light of the findings from this experiment, it is also worthwhile to revisit one of the explanations offered for the absence of a significant learning difference between the response chunked and non-chunked conditions in Experiment 1. One alternative discussed was that participants in Experiment 1 could have spontaneously organized the information within their own self-determined structure, which in the case of the response chunking condition then mismatched with the output format required. However, these results suggest that, contrary to such a notion, if anything a mismatch between the stimulus and response codes would have created more opportunity for the consistent response chunking to improve learning.

EXPERIMENT 4

Although significant gains in learning performance were observed for stimulus chunking, an alternative possible account for such results is that they may be due to the different encoding time allotted in the Stimulus Chunked conditions[3]. For example, given more time to study the groups of information, participants in the Stimulus Chunked condition may be more prone to encode the digits in an integrative fashion. Hence, improved learning may be a function of the time to encode the elements of the sequence rather than chunking per se. The fourth experiment addressed this issue by comparing performance in a Stimulus Chunked condition, featuring the same method as that of Experiment 1, with a modified No Chunking condition in which total study time for each digit was increased to 3 seconds.

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[3] We are grateful to a reviewer, Eric Soetens, for highlighting this possibility.

METHOD

Participants

Seventy-eight participants were recruited from students obtaining partial credits for a General Psychology class.

Procedure

The procedure used for the Stimulus Chunked and No Chunking conditions mirrored that used in Experiment 1 except that in the No Chunking condition, the onscreen time for each digit was 3 seconds (rather than 1 second).

Design

Again every third trial featured a repetition of an identical sequence of digits, with learning assessed by comparing the repeating sequence to the new sequences present on the other trials.

Participants were randomly assigned to one of two stimulus presentation conditions (as used in Experiment 1), either with individual presentation of the nine single digits, each for 3 seconds ("No Stimulus Chunking"), or with chunked presentation of three sets of three digits with each chunk viewed for 3 seconds ("Stimulus Chunked").

RESULTS

A mixed ANOVA of digit series type ("Repeated", "New") by stimulus chunking condition ("No Stimulus Chunking", "Stimulus Chunked") was conducted.

There was a significant main effect of chunking condition ($\underline{F}(1,76)=5.63$, $\underline{p}<.05$, MSE =.123, partial $\eta^2 = .07$; proportion with all nine correct: No Stimulus Chunking = .28, Stimulus Chunked =.42). A main effect of series type was also found

($F(1,76)=67.97$, $p<.05$, MSE =.036, partial $\eta^2 = .47$), with greater recall for repeated series compared to the novel series, showed learning had occurred (proportion of trials with all nine items correct: Repeated = .47, New = .22).

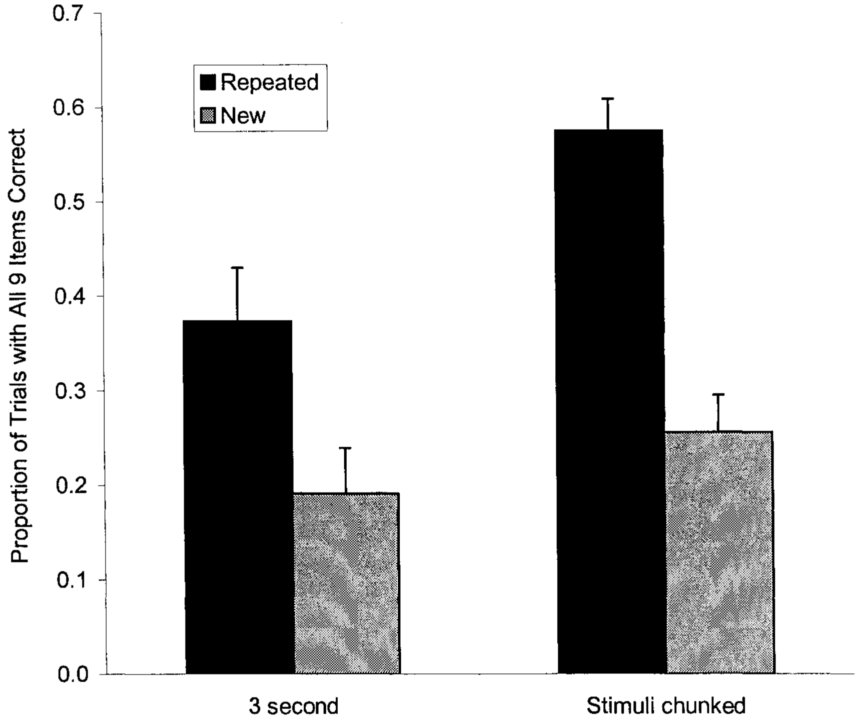

Figure 2.4 Recall performance for random ("new") versus reoccurring ("repeated") series of digits as a function of time to process the digits in 3 Second (digits presented individually at a rate of 1 digit for 3 sec, with responses unstructured) and Stimulus Chunking conditions (digits presented in chunks of three at a rate of 1 chunk for 3 seconds, with responses unstructured).

The critical finding was a significant interaction between series type and chunking condition ($F(1,76)=5.04$, $p<.05$, partial $\eta^2 = .07$; see Figure 2.4). For the new series of digits, no statistically significant differences between stimulus formats was present ($\underline{F}(1,76)=1.60$, $\underline{p}>.05$, MSE =.052, partial $\eta^2 = .02$). However, for the repeating series an advantage for the chunked stimuli was found ($\underline{F}(1,76)=7.37$, $\underline{p}<.05$, MSE =.107, partial $\eta^2 = .09$), once again demonstrating that chunking improved learning of the repeating series.

DISCUSSION

The results of Experiment 4 mirrored those from the similar conditions in Experiment 1. The findings demonstrated that learning of the repeated sequence in the Stimulus Chunked condition was significantly greater than learning in the modified No Stimulus Chunking condition, even when the presentation time of the latter was increased. This suggests that learning in the Stimulus Chunked condition could not be solely attributed to a tendency for participants to use the additiona time in the Stimulus Chunked conditions to inter-relate the digits to each other, or some other difference that might have emerged from the increased presentation time.

GENERAL DISCUSSION

The present experiments investigated how stimulus and response chunking influenced serial recall performance in the Hebb Digits task. Previous work has shown that learning in the Hebb Digits task is sensitive to both stimulus processes (e.g., Bower & Winzenz, 1969) and response processes (e.g., Cohen & Johansson, 1967).

Experiment 1 showed that when compared to a non-chunked baseline, significant gains in incidental learning were found only for stimulus chunking.

Consistent chunking of responses produced no significant gains in learning over the non-chunked baseline condition. Furthermore, when both stimuli and responses were consistently chunked, there were no significant improvements in learning performance compared to when only the stimuli were chunked. In other words, the combined chunking of stimuli and responses, in identical groupings, did not significantly boost learning compared to a condition where only stimuli were chunked. The results of Experiment 1 support the hypothesis that stimulus processes contributed more strongly to the organization of learning in the Hebb Digits task. Moreover the contribution of response processes, under conditions where stimuli are presented in consistent groupings, was negligible. Some researchers have used the Hebb Digits task to study the mechanisms by which information is transferred from short-term to long-term memory (e.g., Melton, 1963; Nelson, 1971). Based on the present results, it might be suggested that learning in the Hebb Digits task results from the long-term storage of sequences of perceptual events rather than sequences of action.

Experiment 2 tested the notion that the gains in incidental learning performance attributed to stimulus processes in Experiment 1 might be due to the feeding forward of perceptual structure onto motor processes. In other words, the chunks developed at encoding would influence the organization of responses such that participants would respond in motor chunks that matched the organization of the stimulus chunks. By introducing a random response structure, whereby participants were required to emit their responses in partial chunks that varied throughout the experiment, participants were prevented from preparing responses consistent with the format developed at encoding. The results, indicating a persistence of learning under conditions of random responding, further verified that stimulus processes drive performance in the Hebb Digits task independent of the response structure. Moreover, Experiment 2 would be consistent with the idea that the chunks developed at encoding are fairly flexible structures that can be decomposed, through working memory processes, into smaller chunks without disrupting learning. Additional confirmation of the dominance of presentation structure in Hebb Digits learning was found in Experiment 4 which ruled out the possibility that the stimuli chunked condition simply provided extra digit encoding time.

Although Experiments 1 and 2 demonstrated a negligible role for response chunking processes in Hebb Digits learning, Experiment 3 identified some specific conditions under which response chunking enhanced such learning. When stimuli were presented in the form of random chunks, learning was observed both with and without response chunking. The fact that response chunking improved performance suggests some role for response-based information in learning. Whether this reflects learning that was absent in the presence of stimulus regularity cannot be resolved on the basis of these data. However, several views of other forms of implicit learning implicate parallel systems (e.g., Keele et al., 2003; Verwey, 2003a, 2003b). By such accounts while multiple forms of learning may always be present, the expression of learning in performance at any time reflects only a single system.

Chunking and response preparation

The interesting question that follows from the results of these experiments is why response chunking does not significantly improve learning once stimulus chunking has structured the information. Although Cunningham et al. (1984) suggest that responding, by functioning as an extra rehearsal opportunity, enables more elaborative processing of the information, the present results suggest a caveat to that idea –namely that response processes cannot further elaborate on the organization developed at encoding to boost learning. According to this view, stimulus characteristics may be responsible for developing the associations among items during encoding and preparing the sequence of responses according to these associations. This idea is consistent with the view that serial learning of repeated information relies mainly on rehearsal during encoding for establishing the associations among items with later rehearsal serving only a maintenance function (Nairne, 1983).

It is likely that the format of the Hebb Digits task underlies the greater importance of the structure of the stimuli. In the present experiments, participants responded on the basis of information retrieved from memory. In contrast, when participants respond to previously learned information that is visible on a computer screen, clearer response-based learning has been found (Fendrich et al., 1991) and chunking effects are confined to response structures (Koch & Hoffman, 2000). However, even in the Hebb Digits task, when structured encoding of the input is disrupted, as in Experiment 3, learning can apparently utilize response processes to form the associations among items. Thus, Hebb Digits task learning can be based either on stimulus or response processes depending on the consistency of the input. When the input is consistent, stimulus processes dominate rehearsal, but when the input is inconsistent, response processes influence rehearsal.

The role of awareness

As discussed in the introduction to this paper, the Hebb Digits task has been classified as an implicit learning task (Seger, 1994; Stadler, 1993), and gains in performance for the repeated series have been reported in the absence of conscious awareness of the repetition (McKelvie, 1987). However, some participants do become aware of the presence of the repeated series. For example, in his seminal paper, Hebb (1961) noted that 25 of his 40 participants were aware of the repeated digit string (see also, Stadler & Roediger, 1998).

The nature of the relationship between implicit and explicit learning remains an issue of some debate (see, Frensch & Rünger, 2003). Nonetheless one mechanism that provides an explanation of the present results would be that the different chunking conditions had different effects on awareness. Specifically, stimulus chunking might produce greater awareness, which in turn leads to superior performance.

While it has been suggested that many forms of implicit learning share similar fundamental characteristics (Reber, 1989), matching the current findings, Seger (1994) has pointed out that the mechanisms operating in different forms of implicit learning appear to be sensitive to different types of information. The operation of these mechanisms in turn will depend on differential contributions from particular brain regions. Learning in the Hebb Digits task is characterized by relatively little responding, which would be consistent with the notion that Hebb Digits learning is not likely centered on the response aspects of performance. Indeed Graybiel (1998) identified one of the defining properties of motor learning as slow acquisition. Thus, one of the characteristic properties of the Hebb Digits task, namely its relatively faster acquisition, implicates a non-motoric neuroanatomical system in learning. One such candidate would be the prefrontal cortex, which is presumed to play a dominant role in working memory processes (Funahashi, 2001; Miller & Cohen, 2001). Interestingly, in terms of the development of awareness, Crick & Koch (1998; Koch & Crick, 1994) highlight a central role for the prefrontal cortex in this process. Additionally, in a review of SRT learning, Willingham (1999) has suggested that the development of explicit awareness during sequence learning may involve areas of the prefrontal cortex.

It remains a question for future research as to whether it is the interplay of specific cortical networks that gives rise to awareness, which would raise the possibility that chunking might act to change the interactions of those areas; or whether processes like chunking might operate in a less direct fashion, such as by decreasing the quantity of cognitive resources required for the task at hand, thereby increasing the resources that can be devoted to developing conscious knowledge of repeating information.

Differences in the effects of stimulus versus response chunking in these experiments might also be traced to the two forms of chunking identified by Gobet and colleagues (2001), i.e., response chunking seems closer to the concept of the automatic form of chunking that Gobet identifies, whereas stimulus chunking appears to be more closely related to the strategically controlled form. However, since both strategic and relational patterns have been shown to influence motor sequence production (Povel & Collard, 1982; Restle, 1970; Restle & Burnside, 1972), there would no inherent reason to believe each form of chunking should be limited in its influence on awareness to either response or stimulus structures. Moreover, there are surface level similarities in the effects of the two forms of chunking, and there is little in the way of direct evidence to determine the relationship between the mechanisms of chunking that arise within the two modes (Gobet et al., 2001).

While the current studies have highlighted that stimulus characteristics can play a dominant role in incidental learning, the issue of whether task differences or chunking differences determine the relative influence of stimulus or response chunking remains a question for future research.

CHAPTER THREE

CHUNKING AND AWARENESS IN THE HEBB DIGITS TASK

As awareness for sequence repetition was never assessed in the experiments reported in Chapter Two, it was unknown whether perceptual chunking produces gains in awareness for sequence repetition. The experiments reported in Chapter Three were designed to investigate whether perceptual chunking increases awareness for the repeated sequence which, in turn, leads to enhanced learning. As a result, multiple measures were used to assess the extent of awareness under No Chunking, Response Chunked and Stimulus Chunking conditions. Three types of awareness, commonly studied under incidental learning conditions, were assessed: Verbal Awareness, Recall Awareness, and Recognition Awareness.

Awareness and encoding processes

The development of awareness during performance in the Hebb Digits task may be linked more to processes occurring at digit encoding than at digit retrieval. This is suggested by the results of Experiment 2 in Chapter Two in which Hebb Digits learning is still possible under conditions of random responding. In contrast, when the stimuli were randomly organized in Experiment 3 of Chapter Two, learning in the Response Chunked condition was not significantly different than in the baseline No Chunking condition. An account based on changes in awareness may also be feasible based on Bower and Winzenz's (1969) reallocation hypothesis. Specifically, the reallocation hypothesis suggests that consistency in the form of the digits during encoding strengthens the memory trace by enabling easier access to the memory location where the digits are stored. Moreover, with increased exposure to the repeated sequence, the "similarity of coding determines recognition of identity" or explicit knowledge of the presence of the repeating sequence (Bower & Winzenz, 1969; p. 16). Thus, the perceptual encoding of each occurrence of the repeated sequence reactivates the stored trace of this sequence and such a pattern of repeated activation may trigger the development of explicit awareness of the repeating digit sequence.

Associative and maintenance rehearsal. The format of the Hebb Digits task involves two temporal points at which rehearsal of the digits occurs: during encoding when the digits are presented and during retrieval when responses are being made. Nairne (1983) has distinguished between two forms of rehearsal: associative rehearsal and maintenance rehearsal. Specifically, Nairne has theorized that associative rehearsal aids in the strengthening of pairwise associations among elements in a string of information, whereas maintenance rehearsal simply functions in keeping the information active. Interestingly, Nairne has suggested that associative rehearsal occurs during the encoding process and maintenance rehearsal occurs during the retrieval process. Based on Nairne's distinctions between associative and maintenance rehearsal, it would seem likely that the associative rehearsal occurring during encoding processes would function more in the strengthening of the pairwise associations that are theorized to lead to the strengthening of the memory trace for the repeated sequence (Lewandowsky & Murdock, 1989). Thus, the greater associative rehearsal occurring when the digits are perceptually encoded may, in turn, lead to a higher probability for increased awareness of the repeated digit sequence.

Chunking and Awareness. The process of chunking has been found to be an important mechanism for learning in another task that features the acquisition of repeated information, artificial grammar learning (Servan-Schreiber & Anderson, 1990). However, depending on task constraints, chunking may not always be the dominant process in artificial grammar learning (Meulemans & Van der Linden, 1997). Chunking has also been found to contribute to the development of explicit knowledge about repeated sequences of information in the serial-reaction time task (SRTT) (Schlaghecken, Stürmer, & Eimer, 2000). Chunking may also play a role in Hebb Digits learning. As mentioned in Chapter One, the extent of digit span may account for Hebb Digits learning as amnesiac patients were able to learn under low digit span conditions (Baddeley & Warrington, 1970), but not under high digit span conditions (Charness, Milberg, & Alexander, 1988; Milberg, et al., 1988). Chunking, which would function to recode a large amount of smaller units of information into fewer larger groups of information and thus, increase digit span would not only benefit Hebb Digits learning, as has been demonstrated (O'Shea & Clegg, in press), but would likely increase explicit knowledge of the repeated sequence.

Awareness and stimulus-chunked vs. response-chunked organization. Based on Bower and Winzenz's (1969) reallocation hypothesis and Nairne's (1983) work on the rehearsal process, it might be expected that chunking of the perceptual input would not only strengthen learning of the digit sequence, but would enable easier digit encoding and thereby facilitate recognition of the repeated digit sequence.

Furthermore, chunking of the perceptual input would induce greater awareness of the repeating digit sequence due to the stronger associations among sequence elements that would develop through associative rehearsal. In other words, presenting the digits in already established chunks accelerates the process by which the pairwise associations among digit sequence elements are strengthened and the sequence comes to be recognized as familiar with repeated exposure. In contrast, chunking of the responses might not increase awareness of the repeated digit sequence since the strength of the trace in memory would be based on the initial perceptual encoding of the sequence which was in a non-chunked form. Moreover, response chunking, according to Nairne's model, would be characterized as a form of maintenance rehearsal and therefore, would not contribute to the strengthening of the pairwise associations among sequence elements. As a result, the greater learning through stimulus chunking, compared to response chunking, in the Hebb Digits task may be due to the increased awareness that develops for the repeated digit sequence in the stimulus-chunked condition.

In summary, perceptual chunking in the Hebb Digits task is theorized to result in greater explicit awareness of the repeated digit sequence than response chunking for the following reasons: 1) Bower and Winzenz's (1969) reallocation hypothesis considers recognition of the repeated sequence to result from repeated exposure to the same processes occurring during perceptual encoding, 2) associative rehearsal during perceptual encoding results in stronger connections among sequence elements that will, in turn, lead to recognition of the sequence than the non-associative maintenance rehearsal that occurs during retrieval, and 3) chunking of the perceptual input will decrease digit span and accelerate the strengthening of associative connections and thus, recognition among sequence elements more than chunking of the response output.

Implicit and explicit distinctions in learning

An important issue currently facing researchers in psychology concerns the role of consciousness in learning. Accordingly, researchers have suggested that the products of a given learning experience may reflect the operation of both implicit and explicit processes (Allwood, Granhag & Johansson, 2000; Frensch & Rünger, 2003; Jacoby, 1998 Whittlesea & Wright, 1997). The term ‘explicit’ is used to characterize a learning experience when the knowledge acquired during learning is consciously available to the learner. In other words, the learner, after completing the task, is cognizant of having learned and can accurately describe what was learned during the task. Explicit learning has been variously operationalized as “hypothesis-driven learning” (Frensch & Rünger, 2003; p.13), learning involving “consciously controlled processes” (Jacoby, 1998; p. 3), “declarative” learning (Cohen & Squire, 1980: p.207; Shimamura & Squire, 1989:p. 722; Squire, 1992: p. 232) and learning resulting in “meta-cognitive knowledge” (Allwood, Granhag & Johansson, 2000; p.166). Interestingly, the above descriptions of explicit learning may also be reflective of a variety of forms of explicit learning.

Conversely, the term ‘implicit’ is used to characterize a learning experience when the acquired information cannot be consciously expressed by the learner subsequent to task performance. Thus, the implicit learner is neither cognizant of having learned anything nor able to report on exactly what was learned during the task. Like explicit learning, implicit learning may consist of different forms and has also been variously defined as knowledge that is "not fully accessible to consciousness" (Seger, 1994; p. 164), learning involving "automatic uses of memory" (Jacoby, 1998; p. 3), learning performance based on an "unintentional retrieval strategy" (Butler & Berry, 2001; p. 192), "procedural learning" (Cohen & Squire, 1980; p. 207), "nondeclarative learning" (Shimamura & Squire, 1989; p. 722; Squire, 1992; p. 232) or "the ability to adapt to environmental constraints-to learn-in the absence of any knowledge about how the adaptation is achieved" (Frensch & Rünger, 2003; p.13). One of the necessary corollaries of a view espousing the joint operation of implicit and explicit processes in learning is that it may be challenging to find a task that reflects pure implicit learning as any given implicit task may be contaminated with explicit processes (Shanks & St. John, 1994). Indeed, some researchers have suggested that the concept of "implicit memory may have outgrown its usefulness as an overall descriptor" (Butler & Berry, 2001; p. 192).

One way to conceptualize the joint presence of implicit and explicit processes in learning is through Tulving's (1985) theory that learning may reflect specific forms of consciousness associated with the given memory system used to represent the information. Specifically, Tulving has suggested that the procedural, semantic and episodic memory systems which represent, respectively, perceptual-motor, symbolic and personally experienced information are characterized by different levels of consciousness. The operation of procedural memory is associated with anoetic consciousness or a non-knowing form of awareness in which the knowledge acquired during the task is restricted to the perceptions and experiences of the task environment. Semantic memory utilizes the noetic form of consciousness in which awareness is associated with the cognitive operations that can be performed on the objects and events that are part of the task. Finally, episodic memory is associated with the autonoetic or self-knowing form of consciousness in which an individual's experience of remembering is integrated with such subjective information as the individual's identity and their subjective experience of time from recall of past experiences to the conception of future episodes. As any given recollective experience is likely to be based on information represented in all of these memory systems, Tulving's theory relating the operation of specific memory systems to different varieties of consciousness provides a viable theoretical approach to understanding how the products of a given learning experience can reflect the operation of both implicit and explicit processes.

Neuroanatomical Substrates of Consciousness. Tulving's (1985) theory that the memory processes representing information are linked to distinct forms of consciousness leads to more fundamental questions regarding the neural nature of consciousness. For example, are there distinct brain regions associated with the operation of implicit and explicit processes in learning? Or do implicit and explicit processes engage all areas of the brain, but to differing degrees? In other words, is the storage of information in the brain, via implicit and explicit processes, the result of anatomical or computational distinctions or some combination thereof.

The hippocampus. The hippocampus, a limbic system structure located in the medial temporal lobe of the brain, has been widely implicated as the cortical region responsible for storing learned information through clinical studies of amnesia

(Penfield & Milner, 1958; Scoville & Milner, 1957), investigations using animal models (O'Keefe & Nadel, 1978; Olton, 1983), computational modeling studies using neural networks (McClelland, McNaughton, & O'Reilly, 2002; O'Reilly & Norman, 2002; Samsonovich & Giorgio, 2005), and functional magnetic resonance imaging (fMRI) studies (Greenberg, et al., 2005). Theoretically, the hippocampus is considered to integrate episodic memories with semantic memories as well as to mediate the distribution of memories to other cortical structures such as the temporal and frontal lobes (Eichenbaum, 2004). It has been suggested that hippocampal interactions with the temporal and frontal lobes may not only determine whether learning occurs, but also whether this learning is accompanied by awareness (Manns, Clark, & Squire, 2000).

Activity in the medial temporal lobe (MTL) has been found to be important in learning with awareness (Clark & Squire, 1998; Hamann & Squire, 1997). More recently, using positron emission tomography (PET), which uses radioactive isotopes to track blood flow changes in the brain, it has been found that the learning performance of aware and unaware participants can be dissociated through the measured activity in the MTL (McIntosh, Rajah, & Lobaugh, 2003). Specifically, McIntosh et al. had participants respond with a particular keypress to the appearance of a visual event that was preceded by one of two tones. One tone served to predict the appearance of a specific visual event while the other did not. During the task, McIntosh et al. observed that the performance of some participants, who became aware of the relationship between the tones and the visual events, was facilitated through faster keypresses, whereas the performance of the unaware participants was not similarly facilitated. Furthermore, McIntosh et al. observed that MTL activity was greater for the aware than unaware participants. The aware participants also exhibited greater activity in brain areas interconnected with the MTL such as the dorsolateral prefrontal cortex (DLPFC) and the lateral occipital cortices. In contrast, the brain regions activated during the performance of the unaware participants were restricted to a more limited network comprising the contralateral MTL regions and the thalamus. However, activity changes in the prefrontal cortex were only observed in the aware participants. This pattern of results is consistent with other studies that have implicated the prefrontal cortex in awareness (Boussaoud, di Pelligrino, & Wise, 1996; Lumer & Rees, 1999). Thus, McIntosh et al.'s results suggest that the development of awareness during a learning task requires some form of interaction between the MTL and the prefrontal areas of the brain and suggest that the degree to which a given product of learning is based on implicit or explicit processing is related to the involvement of the prefrontal cortex in that learning Interestingly, Moscovitch (1995) has suggested that the MTL serves as a site that facilitates the transition of learned information from an implicit to an explicit state.

Although McIntosh et al. (2003) found that awareness for sequence repetition produced faster keypresses and activated different brain regions in a primarily motor-based task, they assessed awareness only through a post-test questionnaire. Such a questionnaire may not be sensitive to the range of conscious knowledge that may develop during task performance. In other words, participants may not be able to verbalize the knowledge that they have learned during a task, but may demonstrate such knowledge in other ways such as recognizing sequence repetition. Thus, McIntosh et al.'s results suggest that while awareness for sequence repetition may facilitate performance via the activation of the prefrontal cortex, it is important to develop measures that comprehensively assess awareness. The next section discusses some of the issues that are important in developing a comprehensive measure of awareness. Since research has shown that learning in the Hebb Digits task can potentially be an implicit process (Baddeley & Warrington, 1970; McKelvie, 1987; Seger, 1994; Stadler, 1989), it is important in the present study to be able to thoroughly assess awareness for sequence repetition.

Criteria for demonstrating awareness.

The issue of determining the proper method by which to distinguish implicit from explicit knowledge has been very contentious among researchers (e.g., Perruchet & Amorim, 1992; Shanks & Johnstone, 1998; Shanks & St. John, 1994; Stadler & Roediger, 1998; St. John & Shanks, 1997). In an extensive review of the literature on implicit learning, Shanks and St. John (1994) offered two criteria that must be satisfied in order to validly assert the existence of unconscious learning in a given task: the Information Criterion and the Sensitivity Criterion. The Information Criterion is derived from the two-part structure of implicit learning tasks which consist of the performance of a task followed by a test that measures the learner's level of awareness. According to Shanks and St. John, the information revealed by the awareness test must be the same information that is responsible for the performance changes during the task. In other words, participants are not simply learning a way to respond on the awareness test that is separate from the knowledge that they have developed during performance or have knowledge from the experiment that is not reflected by their performance on the awareness test. Shanks and St. John's second criterion, the Sensitivity Criterion, is the idea that the test of awareness is appropriately sensitive to all of the conscious knowledge associated with task performance. For example, if participants have learned fragmentary knowledge about the task that aids performance, the awareness test must be able to provide an assessment of the level of fragmentary knowledge that has been learned. Thus, according to Shanks and St. John, assessments of the degree of implicit learning associated with task performance must meet both the Information and Sensitivity Criteria.

Methods for Assessing Awareness. The idea that explicit awareness of the repeating digit sequence may be boosted by chunking of the stimuli rather than chunking of the responses points to an important distinction regarding awareness: how will awareness be defined? As explicit awareness represents the degree of knowledge acquired during the task, there are several ways in which awareness can be assessed. Based on a review of the role of awareness in learning, Shanks and St. John (1994) have identified three techniques that are commonly used for the assessment of awareness. First, awareness can assessed using participants' self reports of their knowledge of the regularities in the presentation of stimuli that occurred in the experiment. Second, participants can be informed that there was a repeating sequence of digits present in the experiment and asked to recall or generate this sequence. Third, participants, once informed of the presence of the repeating sequence, are asked to recognize or select the repeating sequence from a number of possibilities. Additionally, it has been shown that the extent of awareness can be assessed through measures of participants' confidence ratings (Allwood, Granhag, & Johansson, 2000; Dienes & Altmann, 1997; Dienes, Altmann, Kwan & Goode, 1995; Reber & Allen, 1978; Reber, Kassin, Lewis & Cantor, 1980). Thus, explicit awareness can be measured through verbalizable knowledge obtained through self-reports, knowledge that can be recalled or generated, and recognition knowledge.

The Process-Dissociation Procedure. One method for assessing the extent of awareness for information learned is the process dissociation procedure (PDP) first introduced by Jacoby (1991). The PDP is based on the idea that the information learned in a given task is based on both implicit and explicit mechanisms. Therefore, the format of the PDP attempts to separate out the particular implicit and explicit contributions to performance. In particular, Jacoby characterizes implicit mechanisms as those that exert automatic influences on memory, whereas explicit mechanisms involve the controlled use of memory processes. In a typical use of the PDP, participants will be presented with a list of words to study. After the study phase which usually consists of the words being presented individually on a computer monitor at the rate of about 1 word/sec, a testing condition follows in which the participants must complete a series of word stems. Each word stem is preceded by either the prompt *old* or *new.* For word stems preceded by the old prompt, participants are instructed to complete these word stems using only words that were presented during the study phase. This condition is referred to as the inclusion test. For inclusion performance, Jacoby (1998) has developed a mathematical equation to represent the probability (Ri (inclusion) of recollecting a given word:

$$\text{Ri (inclusion)} = E + I - EI$$

where E represents the influence of explicit processes and I represents the influence of implicit processes. Thus, a word could be recollected because it was remembered from the study phase (E) or because it automatically came to mind and seemed familiar (I).

In the exclusion test, participants, presented with the new prompt, are instructed to complete the word stems using only words that did not occur during the study phase. For exclusion performance, the probability of recollecting (Re (exclusion)) a word is given by the following equation:

$$Re = I - EI$$

where once again E represents the influence of explicit processes and I represents the influence of implicit processes. Thus, in the exclusion condition participants would only be able to complete a stem with an old word if the old word came automatically to mind or was retrieved implicitly.

According to Jacoby (1998), the probability of recollection (Rp) can be expressed by the following mathematical equation:

$$Rp = Ri - Re$$

in which Rp represents the probability of recollection, Ri represents the probability of recollection under inclusion conditions and Re represents the probability of recollection under exclusion conditions. Thus, Jacoby's process dissociation procedure enables the empirical determination of the extent to which recall performance is influenced by implicit and explicit processes.

The assumption of process purity. Importantly, Jacoby's (1991) PDP satisfies Shanks and St. John's (1994) information criterion since the knowledge acquired during the study phase is responsible for the difference in performance across the exclusion and inclusion tests. In this sense, it is unlikely that participants are learning anything new on the exclusion and inclusion tests that will affect their performance on these tests. Furthermore, Jacoby's PDP also satisfies Shanks and St. John's sensitivity criterion in that by having participants complete word stems, it enables the use of fragmentary knowledge to aid performance. Thus, it may be possible that the knowledge developed during a continuous task is not brought to bear on a task involving the completion of fragments. However, Jacoby's PDP is based on the assumption of process purity or the idea that recollection involves both implicit and explicit processes and that there are no tests that can purely assess the separate contributions from implicit and explicit knowledge. In other words, implicit and explicit processes both contribute independently to performance and do not interact. The assumption of process purity runs is consistent with the views of a number of theorists who argue that performance in a given task reflects the combined influence of both implicit and explicit processes (Frensch & Rünger, 2003; Perruchet & Amorim, 1992; Whittlesea & Wright, 1997; Willingham & Goedert-Eschmann, 1999). Despite these views, there have been a few studies that have provided evidence for the independence of tasks and processes (e.g., Graf & Mandler, 1984; Schmitter-Edgecombe, 1999) although these studies have not been without their critics (Reingold & Toth, 1996). Thus, although there are still some issues surrounding its use, Jacoby's PDP may still be a useful technique to investigate the influences of implicit and explicit processes on learning provided one makes the assumption that the implicit and explicit processes affecting performance are independent and do not interact.

Recently, Jacoby's (1991) PDP has been successfully applied to the assessment of awareness in the serial-reaction time task (SRTT). In the SRTT (Lewicki, Czyzewska, & Hoffman, 1987; Nissen & Bullemer, 1987; for a review, see Clegg, DiGirolamo, & Keele, 1998), participants are asked to press a key that corresponds to the spatial location of a stimulus that appears on a computer monitor. Unbeknownst to participants, the locations at which the stimuli appear will occur in a repeating pattern during a portion of the task. As a result, the reaction times (RTs) for keypresses will progressively speed up with increased exposure to the repeating pattern and will slow down with exposure to a different pattern. Faster responses to the repeating pattern of stimuli are taken as evidence that participants have learned the repeating pattern and can anticipate the spatial location where the stimulus will appear. However, some participants are generally not able to verbalize what they have learned during the task (Curran & Keele, 1993; Willingham, Nissen, & Bullemer, 1989) nor are they able to demonstrate sequence knowledge in a later prediction task which requires correctly selecting the next element in the sequence subsequent to being presented with one of the items (Nissen & Bullemer, 1987; Stadler, 1989).

Destrebecqz and Cleeremans (2001) modified Jacoby's PDP in order to assess participants' level of awareness of the repetition in the SRTT. In a recall or generation task that occurred immediately after task performance, Destrebecqz and

Cleeremans informed participants that the stimuli they had responded to occurred in a repeating pattern. Participants were then presented with a stimulus from the experiment and asked to generate the succeeding pattern of stimuli for a total of 96 trials using the knowledge they had acquired of the repeating or training sequence. This was the equivalent of Jacoby's inclusion condition. Following their performance in the generation task under inclusion conditions, participants were then asked to perform the same task under exclusion instructions such that they now had to avoid generating the repeating pattern of stimuli for 96 trials. In addition to their modification of Jacoby's PDP to assess recall awareness, Destrebecqz and Cleeremans also assessed participants' recognition awareness of the repeating pattern following a procedure recommended by Shanks and Johnstone (1999). In this procedure, participants were presented with three trial fragments of either the repeating sequence or a random sequence from the experiment and they were required to respond to these stimuli. Additionally, participants were required to rate how confident they were that the fragment was part of the repeating sequence using a 6-point scale ranging from 1 (very certain that fragment was part of the repeating sequence) to 6 (very certain that fragment was not part of the repeating sequence).

Methods for assessing awareness in the Hebb Digits task

The possibility of implicit and explicit mechanisms in Hebb Digits learning makes it difficult to assert whether stimulus chunking solely boosts the degree of explicit learning that occurs in the task or also has some effect on implicit learning. As a result, the present series of experiments will assess awareness of the repeating sequence in the Hebb Digits task along three dimensions: 1) verbalizable knowledge,

2) recall knowledge, and 3) recognition knowledge. Specifically, verbalizable knowledge will be assessed immediately following task performance using three questions (see Appendix A). The first question will feature a free response structure in which participants can voluntarily indicate what, if anything, they noticed about the task. The succeeding questions will feature a forced-choice format in which participants will be required to indicate whether the digit sequences they encountered were predictable or random and the specific format in which the digit sequences were being presented. Additionally, participants will be asked to rate the confidence of their response to the first of the forced-choice questions which asks whether they considered digit presentation during the experiment to be "sometimes predictable" or "always random."

In terms of Shanks and St. John's (1994) criteria for awareness, verbal reports may not adequately satisfy the Information Criterion because as Shanks and St. John (1994; p. 374) have indicated, there is "little reason to believe that the verbal report test provides an exhaustive index of conscious information since there are other tests such as recognition that manifestly detect information left undetected by verbal reports." However, by using several additional measures of awareness such as recall and recognition as well as verbal reports, it may be possible to index a wide range of conscious knowledge associated with task performance. Within this index of the extent of conscious knowledge operating during task performance, the questionnaires may serve to provide an assessment of well-developed complete explicit knowledge.

An additional problem with the use of a questionnaire format to assess conscious knowledge may be that the wording of the questions may have various interpretations for the different participants. For example, in question 2, the option "sometimes predictable" may not be equally descriptive of digit repetition to all of the participants. As Eriksen (1959, p. 203) has noted, the questionnaire format for assessing awareness places "on the individual subject the responsibility for establishing the criterion of awareness." This can be problematic when one considers that different participants may have different criteria for awareness. A further problem with the questionnaire format is that participants who may have been aware of a subset of digits being repeated may not consider this relevant or characterize such repeating subsets as predictable. Butler and Berry (2001) have also noted the limited usefulness of questionnaires in accounting for participants' particular states of awareness when responding during various points in the test. In this sense, Question 2 may not fully meet Shanks and St. John's (1994) Sensitivity Criterion. However, the use of multiple questions, ranging from general to specific inquires on the nature of the task, may improve the extent to which the questions are sensitive to the range of conscious knowledge of the digit repetition present in the task.

Recall knowledge. After the responding to the verbal questions, participants will be informed that there was a repeating digit sequence and will be asked to generate it under inclusion and exclusion conditions. Since the Hebb Digits task involves retrieving a previously viewed sequence from memory, it is likely that those participants who were more aware of the repeating sequence would be more accurate in generating this sequence from memory based on the availability of a single retrieval cue. Specifically, participants will be presented with a target digit, which could be any digit from one to nine, and then, under the inclusion condition, will be asked to type in the digits that followed the target based on their knowledge of which digits followed this target digit in the repeating sequence. Under exclusion conditions, participants will be asked to input the digits following the target digit in a manner that avoids reproducing the digits following this target digit in the repeating sequence. Based on Jacoby's (1991) PDP model, the explicitly aware participants should demonstrate a greater ability to avoid reproducing sequence elements under exclusion conditions than the implicitly aware participants who would have less conscious knowledge of the digits to avoid entering following the target. Overall performance can then be assessed using the following equation:

$$Rs = Ri - Re$$

where the probability of recalling the items of the repeating sequence (Rs) is found by subtracting the number of correctly positioned digits following the target digit reproduced under exclusion instructions (Re) from the number of correctly positioned digits following the target digit under inclusion instructions (Ri). The results of this analysis will yield a score that represents the extent to which participants are explicitly aware of the repeated sequence. Specifically, a higher score would indicate greater awareness or knowledge of the repeated sequence since presumably, more correct digits would be entered under inclusion conditions and less correct digits would be entered under exclusion conditions. Moreover, Jacoby's PDP analysis, by determining the degree to which participants' recall is influenced by implicit and explicit processes, would serve to empirically separate the more aware from the less aware participants. Thus, Jacoby's PDP would make it possible to assess the effects of stimulus and response-based chunking on the development of awareness in the Hebb Digits task. Importantly, Jacoby's PDP analysis would satisfy Shanks and St. John's (1994) Information and Sensitivity criteria by, respectively, assessing knowledge of the same type of information that would be used to account for performance changes during the task and would be sensitive to even fragmentary knowledge that may develop for the ordering of sequence elements.

As mentioned above, Jacoby's PDP is based on the assumption of process purity or that implicit and explicit processes independently influence task performance and that the subtraction of exclusion from inclusion performance will yield a measure of explicit learning. It is important to note that the PDP has a different nature when used with the Hebb Digits task compared to verbal learning tasks. Specifically, the retrieval cue utilized for the Hebb Digits task, a single target digit, has less associative value than the stem of a word which is usually comprised of several letters. As a result, the Hebb Digits task version of the PDP requires that more information be retrieved from memory than in the word-stem completion. Conversely, in the Hebb Digits task, there is only one relevant sequence that is tested with the PDP, whereas in the verbal learning version of the PDP, recall of a number of words from a list is tested using the PDP. Performance on the PDP when applied to the Hebb Digits task may, thus, be a more reliable indicator of the information participants can retrieve from memory since minimal cues are provided and the relevant sequence is tested multiple times.

Recognition knowledge. A further method of assessing awareness in the Hebb Digits task is to determine how well participants are able to recognize an intact nine digit sequence as the repeating sequence. Based on Bower and Winzenz' (1969) idea that similar coding of the repeating sequence each time it occurs mediates its recognition, it is theorized that the process of recognizing the repeating sequence plays a role Hebb Digits performance.

Assessing recognition awareness of the repeating sequence will involve participants indicating whether a single intact sequence presented on the computer monitor was the repeating digit sequence or a novel sequence that had not been previously encountered. In this measure, participants will make a keypress response indicating whether or not they recognize or do not recognize the presented sequence. Specifically, participants will be presented with a total of 5 sequences with 2 of these sequences being previously encountered non-repeating sequences, 2 being completely new sequences that had not been encountered before and 1 sequence will be the repeated sequence. Participants' recognition awareness is determined by whether they correctly recognize the repeating sequence.

In addition to indicating their recognition of the repeating sequence, participants will also be asked to indicate how confident they are of their selections using a 5-point Likert scale. Performance on the recognition task will provide a measure of how well participants can explicitly recognize the repeated sequence as well as how confident they are in this recognition. As with Question 2, confidence ratings can provide additional information on the extent of conscious knowledge of the repetition under the assumption that greater awareness should equate with higher confidence ratings (see also, Berry, 1996; Berry & Dienes, 1993;Dienes & Altmann, 1997; Dienes, Altmann, Kwan & Goode, 1995; Reber & Allen, 1978; Reber, Cassin, Lewis & Cantor, 1980).

Hypotheses

Participants will be classified as either aware or unaware of sequence repetition separately for each of the three measures of awareness outlined above (i.e., verbal, recall and recognition). The present experiments will then test the hypothesis that perceptual chunking in the Hebb Digits task will lead to a greater degree of awareness of sequence repetition across all three of the awareness measures than response chunking. The increased awareness associated with perceptual chunking is hypothesized to be based on the increased opportunity for more elaborative associations among sequence elements to develop when the stimuli are organized than when responses are organized. Moreover, the increased awareness associated with perceptual chunking is theorized to produce greater learning of the repeated sequence in this condition compared to the no chunking and response chunked conditions.

EXPERIMENT 1

In the present experiment, learning and awareness will be examined across three of the conditions from the experiments reported in Chapter 2: a non-chunked baseline condition, a stimulus-chunked condition and a response-chunked condition. From this experiment, it is predicted that the results will replicate those reported in Chapter 2 indicating a significant learning advantage for the stimulus-chunked condition compared to the no chunking condition and the absence of such an advantage for the response chunked condition compared to the no chunking condition. Furthermore, it is expected that verbal, recall and recognition awareness will be greatest in the stimulus-chunked condition than in either the no chunking or response-chunked conditions.

METHOD

Except where noted methodology for the following experiments matched that of Experiment 1 in chapter two.

Participants

One hundred six participants were recruited from students obtaining optional partial credits for a General Psychology class. A total of four participants were dropped from the analyses based on poor performance during the 24 recall trials. Specifically, two of the participants did not respond on any of the trials and the other two participants did not respond on more than half of the trials. All participants provided informed consent. There was no overlap of participants across any of the experimental conditions.

Stimuli and Apparatus

Same as Experiment 1.

Procedure

The procedure matched that used in Experiment 1 in chapter two for the non-chunked, stimulus chunked and response chunked conditions. Additionally, performance in each of these conditions was followed by a three-part test assessing awareness of the repeating digit sequence.

Design

Measures

Scoring Performance. In addition to scoring performance based on the proportion of trials perfectly recalled as used in Experiment 1 of Chapter Two, the method advocated by McKelvie (1987) was also used to score performance. Although McKelvie's scoring system is prone to producing inflated scores compared to left-to-right analyses and the proportion of perfect recall trials, it may be more sensitive to measuring recall performance in situations where participants respond in fragments of the digit sequences. For instance, the performance of participants with less awareness of the repeated sequence may be characterized by fragmentary knowledge whereas those participants with greater awareness of the repeated sequence may demonstrate more complete knowledge of the sequence. Consequently, the McKelvie scoring system, which is sensitive to both fragmented responses and complete responses, would enable assessments of recall performance across a wide range of awareness levels. In contrast, analyses based on scoring digit recall based on the proportion of perfect recall trials may be biased towards the performance of participants who have developed greater explicit awareness of the repeated sequence.

For the analyses conducted with McKelvie's (1987) method, recall performance was examined on Trials 21-24 or the last four trials of the experiment. Specifically, learning was assessed by comparing the mean of the final two trials featuring non-repeated sequences (Trials 22 and 23) with the mean of the final two trials featuring the repeated sequence. The reasoning for this analysis, which omits examination of performance on earlier presentations of the repeated sequence, was that the recall performance for the final two presentations of the repeated sequence would most likely be influenced by explicit awareness of the repeated sequence provided participants had developed such awareness on the earlier trials. Similarly, performance on the non-repeated trials would more likely be immune to the possibility of the practice effect difference between the aware and unaware participants as noted by McKelvie.

Scoring Digit Span. Participants' digit spans were assessed by determining the mean recall score for their performance on all of the non-repeating trials using McKelvie's method (e.g., trials 1,2,3,4,5,7,8,10,11,13,14,16,17,19,20,22, and 23). Participants' mean digit span scores were then used in a later multiple regression analysis to determine the relationship among learning, awareness and digit span across the three chunking conditions.

Assessing Awareness. Three types of awareness, verbal, recall, and recognition, were assessed in the following manner.

Verbal Knowledge. Immediately following task performance, participants were asked three questions, via the computer, in order to evaluate their subjective assessment of the degree to which they were aware of the digit regularities in the task (for the questionnaire, see Appendix A). Participants were provided with as much time as they needed to answer these questions. Each question was presented only after a response had been received to the prior question. Question 1 was a free response question. Questions 2 and 3 were forced choice questions designed to assess participants' specific knowledge of the digit repetition in the experiment. Additionally, for Question 2, participants were asked to rate the confidence of their response on a five point Likert Scale where 1 represents most confident and 5 represents least confident. The awareness measured by Questions 1-3 is considered to be subjective in nature since it is based on participants' self-reports.

Scoring Verbal Knowledge. Participants were classified for verbal awareness based on their response to question 3 (e.g., "*Select the option below that best summarizes the task you just completed").* Participants who selected option c (e.g., "*An entire sequence regularly repeated during the task*") were classified as aware of sequence repetition, while those who selected any of the other options were classified as unaware. Question 3 was selected to classify participants' awareness because it was the most direct of all the verbal questions regarding knowledge of sequence repetition.

Recall Knowledge. After completing the verbal assessment of awareness, participants were informed that a particular sequence was regularly repeated during the experiment and then, upon the presentation of a target digit, were asked to type in all of the digits that followed the target digit in succession up to and including the target digit. In other words, after typing the digits from memory beginning with the digit following the target digit up until the end of the sequence, participants return to the beginning of the sequence in memory and type the digits in order up to and including the target digit.

The recall procedure consisted of two conditions. In the first condition, known as the inclusion condition, participants were instructed to type back digits according to their knowledge of the repeating sequence presented during the experiment. For example, when presented with a particular digit, participants, under the inclusion condition, were required to type all of the succeeding digits in correct order up to and including the target digit based on their knowledge of the repeating sequence from the experiment. Conversely, in the exclusion condition, participants were instructed to refrain from using their knowledge of the repeating sequence from the experiment and instead, typed back the digits that would not have occurred following the target digit in the repeating sequence from the experiment. Additionally, participants were instructed to break up the digits that were grouped together in the repeating sequence so they would not appear together in fragments.

Participants completed 18 inclusion trials followed by 18 exclusion trials based on two opportunities to respond to the nine possible target digits in each condition. The inclusion trials always preceded the exclusion trials in order to maintain the same testing conditions for all participants. In responding to the target digit, participants typed with their dominant hand using the horizontal number row of the keyboard. This procedure assesses participants' awareness of the repeating sequence based on their ability to recall the sequence or generate it under inclusion and exclusion conditions.

Scoring Recall Knowledge. Following Jacoby's (1991) recommendations for scoring PDP data, participants' performance was assessed across the inclusion and exclusion conditions. Specifically, the sequences participants typed following the target digit were scored using the method advocated by McKelvie (1987). The reasoning behind using McKelvie's scoring method is that it has greater sensitivity across a wide range of awareness levels. The extent of participants' explicit awareness was then determined by subtracting participants' mean recall of the digits following the target digit reproduced under exclusion instructions from their mean recall of digits following the target digit under inclusion instructions. The results of this analysis yield a score that represents the extent to which participants are aware of the repeated sequence. Specifically, a higher score on this measure would reflect greater awareness or knowledge of the repeated sequence since presumably, more correct digits would be entered under inclusion conditions and participants would be better able to consciously avoid entering correct digits under exclusion conditions. Participants were classified as aware if their inclusion - exclusion score was 1 or greater and were classified as unaware if their inclusion - exclusion score was less than 1. A score of 1 would indicate that participants were able to consciously recall at least one digit in the sequence correctly, any score below 1 would suggest the absence of conscious influence on recall for all items in the sequence.

Recognition Knowledge. After performing the generation task, participants were again informed that the experiment featured a repeating sequence of digits and were asked to make a keypress response indicating whether or not they recognized a particular nine digit sequence. Specifically, participants were presented with a total of 5 nine digit sequences with 2 of these sequences being previously encountered non-repeating sequences, one from the earlier and one from the later trials of the experiment, 2 being completely new sequences that had not been encountered during the experiment and 1 sequence was the repeated sequence that occurred during the experiment. Participants were required to indicate their recognition of the repeating sequence by pressing the *y* and *n* keys of a standard computer keyboard denoting, respectively, “yes” or “no”. In addition to indicating their recognition of the sequences, participants were also asked to rate how confident they were of their recognition response selections using a 5-point Likert scale (see Appendix B).

Scoring Recognition Knowledge. Participants were classified for recognition awareness based on whether or not they correctly recognized the repeating sequence. Specifically, participants who correctly recognized the repeated sequence were classified as aware and those who did not recognize the repeated sequence were classified as unaware.

Analyses

In order to determine if the results reported in Experiment 1 of Chapter Two were replicated, a mixed ANOVA of digit series type (“Repeated”, “New”) by chunking condition (“No Chunking”, “Stimulus Chunked”, “Response Chunked”) was first conducted. The relationship between learning and awareness was then assessed using a mixed ANOVA of digit series type (“Repeated”, “New”) by chunking condition (“No Chunking”, “Stimulus Chunked”, “Response Chunked”) by awareness (“Aware”, “Unaware”). The point of conducting two separate mixed ANOVAs was to determine if accounting for awareness would change the observed relationship between recall and chunking from Experiment 1 of Chapter Two. Follow-up analyses between chunking conditions were then planned to assess interactions between chunking and awareness. In order to minimize the potential for Type 1 error from inflated familywise alpha, a Bonferroni correction was used during the follow-up analyses. Additional analyses using t-tests were then conducted to compare the recall performance of the aware and unaware participants for each of the awareness measures. The point of these analyses was to determine if there were significant differences in recall performance for the aware compared to the unaware participants. The extent to which chunking increased the number of participants indicating awareness of sequence repetition was then assessed separately for each of the awareness measures using a chi-square analysis.

In order to determine the performance variables that are most closely associated with Hebb Digits learning, a stepwise linear multiple regression was performed with the chunking groups, the three measures of awareness (Verbal, Recall, and Recognition Awareness) and digit span regressed against learning performance. The analysis was performed using SPSS REGRESSION for the evaluation of the assumptions. The results of the regression analysis were then used to determine the factors that accounted for the greatest proportion of total variance.

RESULTS

In order to examine whether chunking provided benefits for recall as seen in Experiment 1 of Chapter Two, a mixed ANOVA of digit series type (“Repeated”, “New”) by chunking condition (“No Chunking”, “Response Chunked”, “Stimulus Chunking”) was conducted. A main effect of series type ($F(1,100) = 64.11$, $p < .05$, MSE = .029, partial $\eta^2 = .39$), with greater recall for repeated series compared to the new series, showed learning had occurred (mean proportion of trials with all nine items correct: Repeated = .32, New = .14). The main effect of chunking condition ($F(2,100) = 11.85$, $p < .05$, MSE = .091, partial $\eta^2 = .192$) was again congruent with the well established advantage of chunked information for the short-term memorization of digits required on each trial in this paradigm (mean proportion of trials with all nine items correct: No Chunking = .24, Response Chunked = .24, Stimulus Chunked = .5).

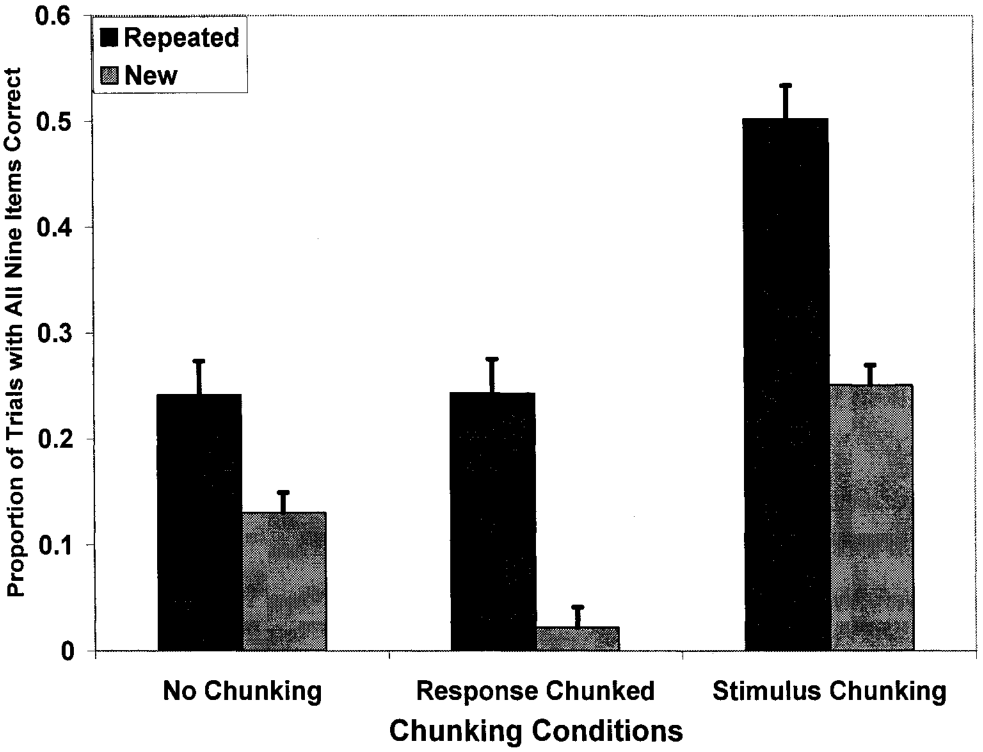

Figure 3.1. Recall performance for random ("new") versus reoccurring ("repeated") series of digits as a function of chunked condition. The three conditions, based on the structure of the stimuli and responses, are as follows: No Chunking (stimuli presented individually/responses unstructured), Response Chunked (stimuli presented individually/responses executed in chunks of three), Stimulus Chunking (stimuli presented in chunks of three/responses unstructured). (Error bars indicate standard error).

Crucially for the assessment of whether learning gained additional benefits from chunking, a significant interaction between series type and chunking condition was observed ($\underline{F}(2,100) = 3.93$, $\underline{p} < .05$, partial $\eta^2 = .073$; see Figure 3.1). Follow-up analyses were then conducted to make comparisions between each of the chunking conditions.

Results for comparisons between chunking groups

For the follow-up analyses reported here, a Bonferroni correction was used to minimize the probability of committing Type 1 error. For the comparison of just the Stimulus Chunking to the No Chunking groups, a significant interaction between series type and chunking condition was found ($\underline{F}(1,71) = 6.96$, $\underline{p} < .017$, MSE $= .029$, partial $\eta^2 = .089$). In the comparison of the Response Chunked group to the No Chunking group, no statistically significant interaction was observed ($\underline{F}(1,68) = 5.34$, $\underline{p} > .017$, MSE $= .023$, partial $\eta^2 = .073$). Similarly, in the comparison of the Stimulus Chunking and Response Chunked groups, there was no statistically significant interaction observed ($\underline{F}(1,61) < 1$, $\underline{p} > .017$, MSE $= .037$, partial $\eta^2 = .003$). Therefore, in accordance with the findings reported for Experiment 1 in Chapter Two, it appears that learning benefits from chunking of the stimuli, although there was some indication of a benefit from chunking of the responses this did not reach statistical significance. In summary, these results are in general agreement with the results reported in Chapter Two with only stimulus chunking showing clearly increased learning.

The role of awareness

In order to assess whether such gains in learning performance that resulted from chunking interacted with awareness of sequence repetition, or indeed might be explained by awareness, three separate mixed ANOVAs were conducted based on each of the three awareness measures: verbal awareness, recall awareness and recognition awareness.

Recall awareness

Participants were classified for recall awareness based on their inclusion/exclusion score. Specifically, participants were classified as aware if their inclusion/exclusion score was 1 or greater and were classified as unaware if their inclusion/exclusion score was less than 1. Fifty-seven participants were classified as aware and thirty-eight participants were classified as unaware of sequence repetition. Eight participants who did not follow instructions on either the inclusion or exclusion tests or both were dropped from these analyses.

In order to examine whether the previously observed gains in learning produced by chunking were influenced by recall awareness, a mixed ANOVA of digit series type ("Repeated", "New") by chunking condition ("No Chunking", "Response Chunked", "Stimulus Chunked") by recall awareness ("Aware", "Unaware") was conducted. For these analyses, the results indicated a main effect of series type ($\underline{F}(1,89) = 47.97$, $\underline{p} < .05$, MSE = .026, partial $\eta^2 = .35$), with greater recall for repeated series compared to the novel series, showed learning had occurred (mean proportion of trials with all nine items correct: Repeated = .32, New = .21). The results also indicated a significant interaction between series type and recall awareness ($\underline{F}(1,89) = 9.45$, $\underline{p} < .05$, MSE = .246, partial $\eta^2 = .096$). However, unlike the previous analysis comparing recall across the chunking conditions, there was now no significant interaction between series type and chunking condition

($\underline{F}(2,89) = 1.49$, $\underline{p} > .05$, MSE = .039, partial $\eta^2 = .032$). These results suggest that once recall awareness of sequence repetition was accounted for, no further identifiable impact on sequence performance from chunking condition was present. The interaction between series type, chunking condition and recall awareness was not significant ($\underline{F}(2,89) = 1.43$, $\underline{p} > .05$, MSE = .037, partial $\eta^2 = .031$).

The between-subjects analyses indicated a main effect for recall awareness ($\underline{F}(1,89) = 4.16$, $\underline{p} < .05$, MSE = .387, partial $\eta^2 = .045$) and chunking condition ($\underline{F}(2,89) = 10.41$, $\underline{p} < .05$, MSE = .967, partial $\eta^2 = .190$). However, the between-subjects interaction of recall awareness and chunking was not significant ($\underline{F}(2,89) = 1.06$, $\underline{p} > .05$, MSE = .098, partial $\eta^2 = .023$).

Awareness and recall performance. In order to assess whether greater recall for the repeated sequence compared to the new sequences was dependent on having some explicit knowledge of the repeating sequence, the recall performance of the recall aware and recall unaware participants were analyzed separately using paired samples t-tests. For the analysis of just the recall aware participants, the results of the t-test indicated significantly greater recall performance for the repeated sequence compared to the new sequences ($\underline{t\ (56)} = 7.4$, $\underline{p} < .05$; mean proportion of trials with all nine items correct: Repeated = .40; New = .15). Similarly, the results of the t-test analysis for the recall unaware participants indicated that recall performance of the repeated sequence was significantly greater than the new sequences ($\underline{t\ (37)} = 3.0$, $\underline{p} < .05$;

mean proportion of trials with all nine items correct: Repeated = .22; New = .14; see Figure 3.2). In summary, these results suggest that both aware and unaware participants, classified based on the process dissociation task, are able to demonstrate greater recall performance for the repeated sequence compared to the new sequences.

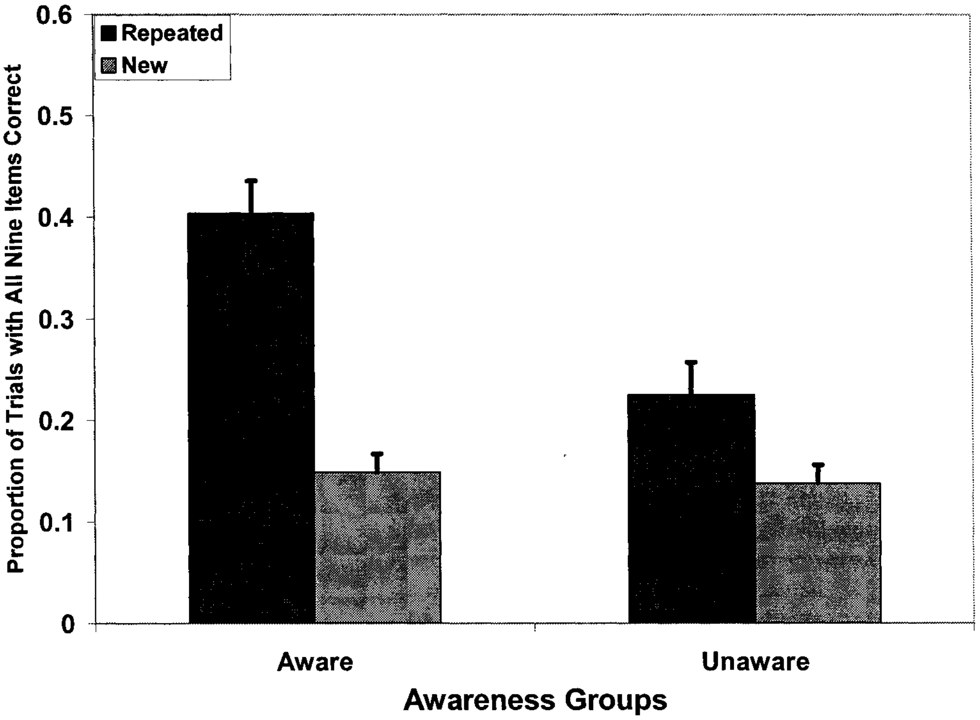

Figure 3.2. Recall performance for random ("new") versus reoccurring ("repeated") series of digits as a function of level of awareness of sequence repetition. Participants with a score of 1 or greater on the inclusion/exclusion test were classified as aware. Participants with a score of less than 1 on the inclusion/exclusion test were classified as unaware. (Error bars indicate standard error).

Recall awareness and chunking. In order to assess whether awareness of sequence repetition was related to the chunking, a chi-square analysis was conducted to compare the number of aware and unaware participants across the chunking conditions. The results of the chi-square analysis, while non-significant, indicated a trend towards chunking producing increases in the number of participants demonstrating awareness of sequence repetition ($\underline{\chi^2(2)} = 5.54$, $\underline{p} = .063$; see Figure 3.3).

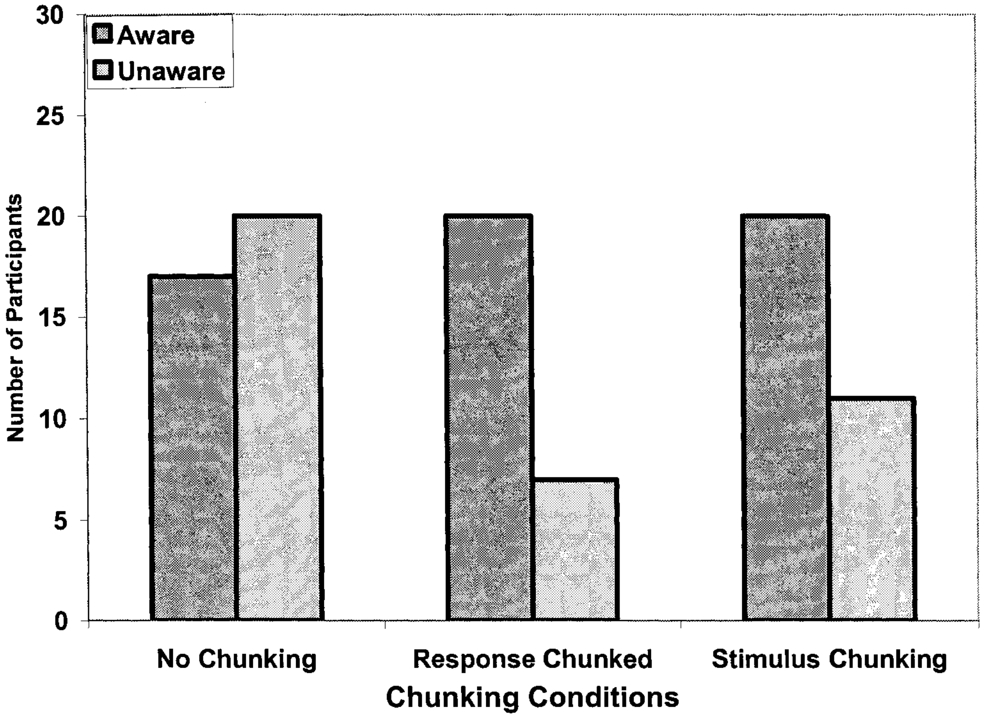

Figure 3.3

Total number of participants who were classified as aware or unaware of sequence repetition across the three chunking conditions. Participants with a score of 1 or greater on the inclusion/exclusion test were classified as aware. Participants with a score of less than 1 on the inclusion/exclusion test were classified as unaware.

Thus, these results would be congruent with the notion that chunking may increase recall awareness of sequence repetition.

Verbal awareness

Participants were classified for verbal awareness based on, respectively, whether they chose option c (e.g., "*An entire sequence regularly repeated during the task*") in response to question three, or chose an option other than c. Sixty-nine participants were classified as aware and thirty-one participants were classified as unaware of sequence repetition. Three participants who did not provide a response to question 3 were dropped from these analyses.

In order to examine whether the gains in learning produced by chunking interacted with verbal awareness, a mixed ANOVA of digit series type ("Repeated", "New") by chunking condition ("No Chunking", "Response Chunked", "Stimulus Chunked") by verbal awareness ("Aware", "Unaware") was conducted. These analyses indicated a main effect of series type ($\underline{F}(1,94) = 34.99$, $\underline{p} <.05$, MSE = .025, partial $\eta^2 = .27$), with greater recall for repeated series compared to the novel series,showed learning had occurred (mean proportion of trials with all nine items correct: Repeated = .32, New = .14). The results also indicated a significant interaction between series type and verbal awareness ($\underline{F}(1,94) = 15.52$, $\underline{p} <.05$, MSE = .386, partial $\eta^2 = .142$). However, again unlike the analysis comparing recall across the chunking conditions only, when this measure of awareness was included there was now no significant interaction between series type and chunking condition ($\underline{F}(2,94) = 1.69$, $\underline{p} >.05$, MSE = .042, partial $\eta^2 = .035$). These results suggest that once verbal awareness of sequence repetition was accounted for, no further identifiable impact on sequence performance from chunking condition was present. The interaction between series type, chunking condition and verbal awareness was not significant ($\underline{F}(2,94) < 1$, MSE = .005, partial $\eta^2 = .004$).

The between-subjects analyses indicated a main effect for verbal awareness ($\underline{F}(1,94) = 15.5$, $\underline{p} < .05$, MSE = 1.2, partial $\eta^2 = .142$) and chunking condition ($\underline{F}(2,94) = 5.99$, $\underline{p} < .05$, MSE = .454, partial $\eta^2 = .113$). However, the between-subjects interaction of verbal awareness and chunking was not significant ($\underline{F}(2,94) = 2.17$, $\underline{p} > .05$, MSE = .164, partial $\eta^2 = .044$).

Awareness and recall performance. In order to assess whether greater recall for the repeated sequence compared to the new sequences was dependent on verbal awareness, the recall performance of the verbal aware and verbal unaware participants were analyzed separately using paired samples t-tests. For the analysis of just the verbal aware participants, the results of the t-test indicated significantly greater recall performance for the repeated sequence compared to the new sequences ($\underline{t\ (68)} = 8.8$, $\underline{p} < .05$; mean proportion of trials with all nine items correct: Repeated = .43; New = .17). Conversely, for the verbal unaware participants, the results of the t-test analysis indicated that recall performance of the repeated sequence was not significantly greater than the new sequences ($\underline{t\ (94)} = .94$, $\underline{p} > .05$; mean proportion of trials with all nine items correct: Repeated = .10; New = .07; see Figure 3.4).

Collectively, these results suggest that the ability to verbally express knowledge of sequence repetition is associated with greater recall for the repeated sequence compared to the new sequences, and that in the absence of such knowledge no significant learning occurred.

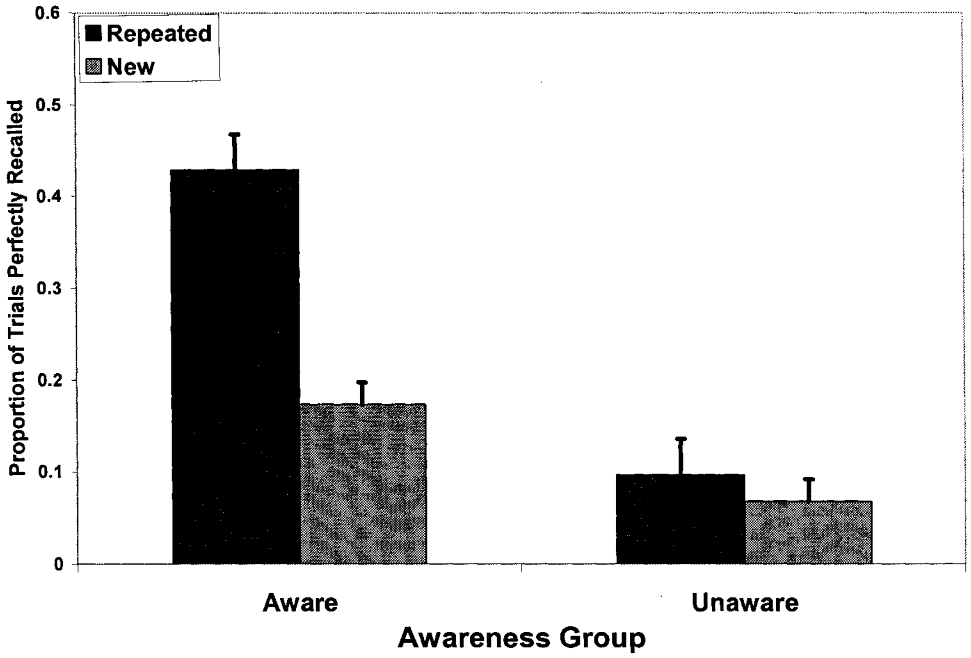

Figure 3.4. Recall performance for random ("new") versus reoccurring ("repeated") series of digits as a function of level of verbal awareness of sequence repetition. Participants who correctly chose option c for Question 3 (e.g., "*An entire sequence regularly repeated during the task") were classified as aware while participants who did not choose option c on Question 3 were classified as unaware. Recall performance was determined by the mean proportion of trials in which all nine digits were correctly recalled. (Error bars indicate standard error).*

Verbal awareness and chunking. In order to assess whether verbal awareness of sequence repetition benefited from chunking, a chi-square analysis was conducted to compare the proportion of aware and unaware participants across the chunking conditions. The results of the chi-square analysis, while non-significant, indicated a trend towards chunking being related to increases in the number of participants demonstrating awareness of sequence repetition ($\chi^2(2) = 5.29$, $p = .071$; see Figure 3.5). Thus, again with this measure of awareness, there was some hint that chunking may increase verbal awareness of sequence repetition.

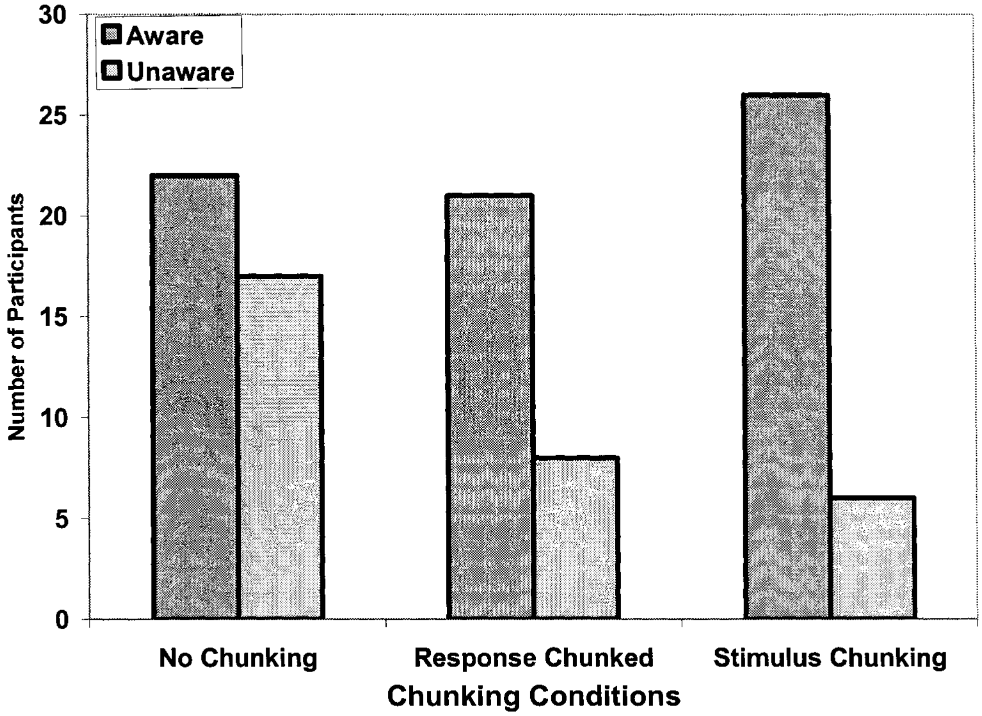

Figure 3.5. Total number of participants who were classified as aware or unaware of sequence repetition across the three chunking conditions. Participants who correctly chose option c for Question 3 (e.g., "*An entire sequence regularly repeated during the task"*) *were classified as aware while participants who did not choose option c on Question 3 were classified as unaware.*

Recognition awareness. Participants were classified for recognition awareness based on whether or not they correctly selected the repeating sequence on a forced-choice recognition test. Sixty-seven participants were classified as aware and thirty participants were classified as unaware of sequence repetition. Six participants who did not respond when instructed to indicate their recognition of the repeating sequence were dropped from these analyses leaving data from 97 participants. In order to examine whether the gains in learning produced by chunking interacted with recognition awareness, a mixed ANOVA of digit series type ("Repeated", "New") by chunking condition ("No Chunking", "Response Chunked", "Stimulus Chunked") by recognition awareness ("Aware", "Unaware") was conducted. The results indicated a main effect of series type ($\underline{F}(1,91) = 47.89$, $\underline{p} < .05$, MSE = .029, partial $\eta^2 = .345$), with greater recall for repeated series compared to the novel series, showed learning had occurred (mean proportion of trials with all nine items correct: Repeated = .32, New = .20). The results also indicated a significant interaction between series type and chunking condition ($\underline{F}(2,91) = 3.55$, $\underline{p} < .05$, MSE = .104, partial $\eta^2 = .072$; mean proportion of trials with all nine items correct: No Chunking = .24; Response Chunked = .25; Stimulus Chunking = .50). However, unlike the previous analyses for verbal and recall awareness, there was no significant interaction between series type and recognition awareness ($\underline{F}(1,91) < 1$, MSE = .002, partial $\eta^2 = .001$). These results suggest that chunking condition,, and not recognition awareness, influenced learning. The results indicated that the interaction between series type, chunking condition and recognition awareness was not significant ($\underline{F}(2,91) < 1$, MSE = .023, partial $\eta^2 = .017$).

The between-subjects analyses indicated a main effect for chunking condition ($\underline{F}(2,91) = 9.91$, $\underline{p} < .05$, MSE = .872, partial $\eta^2 = .179$), but the main effect for recognition awareness was not significant ($\underline{F}(1,91) = 1.64$, $\underline{p} > .05$, MSE = .144, partial $\eta^2 = .018$). Finally, the between-subjects interaction of recognition awareness and chunking was significant ($\underline{F}(2,91) = 3.55$, $\underline{p} < .05$, MSE = .312, partial $\eta^2 = .072$).

In summary, the findings for the interaction of recognition awareness and chunking condition differ from the above analyses which indicated that verbal and recall awareness had a greater impact on recall performance than chunking condition. Hence, in this case further analyses of the aware and unaware participants, as classified by the ability to correctly recognize the repeating sequence, were not conducted. Similarly, further analyses examining the interaction between chunking and recognition awareness were not necessary.

Recognition awareness and chunking. In order to assess whether awareness of sequence repetition benefited from chunking, a chi-square analysis was conducted to compare the proportion of aware and unaware participants across the chunking conditions. The proportion of participants who were classified as aware and unaware for each of the chunking groups was as follows: No Chunking = Aware (60.5%, N = 23), Unaware (39.5%, N = 15); Response Chunked = Aware (77.8%, N = 21), Unaware (22.2%, N = 6), and Stimulus Chunking = Aware (71.9%, N = 23), Unaware (28.1%, N = 9). The results of the chi-square analysis were non-significant indicating that chunking does not produce an increase in the number of participants demonstrating recognition awareness of sequence repetition ($\underline{P}\ (2) = 2.37$, $\underline{p} > .05$; see Figure 3.6).

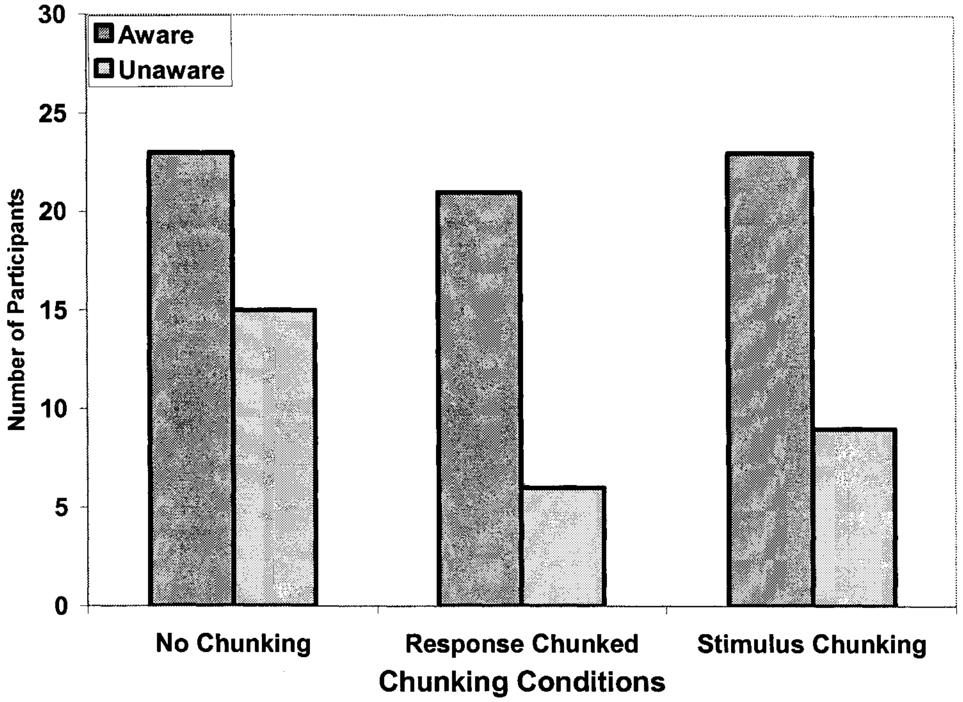

Figure 3.6. Total number of participants who were classified as aware or unaware of sequence repetition across the three chunking conditions. Participants who correctly recognized the repeating sequence were classified as aware while participants who did recognize the repeated sequence were classified as unaware.

Verbal awareness and recall awareness. Of the three measures used to assess awareness, the results reported above indicated that verbal and recall awareness had a similar relationship to task performance. Specifically, participants who were classified as aware, either through verbal or recall measures of awareness, demonstrated a significant recall advantage over participants classified as unaware on these measures. Furthermore, the results of the chi-square analyses indicated a trend toward increasing numbers of participants developing either recall or verbal awareness of sequence repetition with chunking. Thus, based on the similar patterns of performance for verbal and recall awareness, it is of interest to determine whether verbal and recall awareness represent the same underlying form of awareness or independent forms of awareness.

In order to determine whether there is a strong relationship between verbal and recall awareness, a point biserial analysis was conducted using the raw recall awareness scores and the dichotomous classification labels (i.e., "Aware, "Unaware") used for verbal awareness. As noted in the previous analyses, participants were classified as aware or unaware based on, respectively, whether or not they chose option c (e.g., "*An entire sequence regularly repeated during the task*"). In the present analysis, 65 participants were classified as aware and 29 were classified as unaware based on their verbal awareness scores. Eight participants were excluded from these analyses for not properly following the instructions for the inclusion and/or exclusion tasks that were used to derive the recall awareness scores; three of these eight excluded participants also did not enter a response to option c in the verbal measure. The overall mean for recall awareness was 2.24. The mean recall awareness scores for the verbal aware and unaware participants were, respectively, 3.08 and .36. The results of the point biserial correlation indicated that verbal and recall awareness were moderately correlated ($\underline{r} = .44$). The lack of a moderate correlation between verbal and recall awareness suggests that these different expressions of awareness are not identical measures, but that they may have some common underlying basis.

Regression analyses

The results reported above suggest that awareness of sequence repetition, rather than stimulus chunking, is the factor that accounts for Hebb Digits learning. Although the chi-square analyses indicated a trend for chunking to produce increases in awareness for sequence repetition, this trend was only observed for awareness based on either verbal or recall measures. Recognition awareness was not found to be strongly related to Hebb Digits learning. The relative independence of verbal and recall awareness, as determined by the moderate point biserial correlation between these measures, brings up an interesting point: Which of these forms of awareness, verbal or recall, is more important to Hebb Digits learning?

In order to develop a better understanding of the factors that contribute to Hebb Digits learning, a stepwise linear multiple regression was performed between Learning Score as the dependent variable and Chunking Group, Verbal Awareness, Recall Awareness, Recognition Awareness and Digit Span as the independent or predictor variables. Chunking Group consisted of three dummy variables: 1) a No Chunking variable that was dichotomously coded to reflect the presence or absence of chunking, 2) a Response Chunked variable that was dichotomously coded to reflect the presence or absence of response chunking, and 3) a Stimulus Chunking variable that was dichotomously coded to reflect the presence or absence of stimulus chunking. Except for Recall Awareness, which consisted of raw scores, the predictor variables for Recall and Recognition Awareness were coded according to the dichotomous categories of 'aware' and 'unaware' as determined in the above analyses. The variable of Digit Span consisted of participants' mean recall scores for all of the new trials. Finally, Learning Score was derived by subtracting the proportion of perfectly recalled trials for new sequences from the proportion of perfectly recalled trials for the repeated sequence.

The entry of variables into the stepwise regression occurred in the following sequence. First, the three dummy variables for Chunking Group were entered into the model. The entry of Chunking Group as the first variable was designed to minimize the variance associated with the chunking manipulation from affecting the analysis of the other variables. For example, as indicated by the chi-square analyses above, chunking may produce increases in verbal and recall awareness. Furthermore, chunking may increase Digit Span performance.

Table 3.1 displays the correlations between the four predictor variables (Verbal Awareness, Recall Awareness, Recognition Awareness and Digit Span) and Learning Score for the first analysis. Overall, the regression model using these four variables was significant (F(6,93) = 4.39, $p < .05$, MSE = .142). The results of the regression analysis indicated that two of the independent variables contributed significantly to predicting learning in the Hebb Digits task: Recall Awareness and Verbal Awareness. Neither Digit Span nor Recognition Awareness contributed significantly to regression. Altogether, 23% (18% adjusted) of the variability in learning scores on the Hebb Digits task were predicted by the scores on these four independent variables. The results of the regression analyses are in agreement with previous analyses indicating that learning in the Hebb Digits task is mediated by Recall Awareness and Verbal Awareness.

Table 3.1

Results of Stepwise Linear Regression Analyses with Learning Score as the Dependent Variable and Verbal Awareness, Recall Awareness, Recognition Awareness, and Digit Span as Predictor Variables

	Learning Score	
Predictor Variables	t	R^2
Verbal Awareness	2.74**	.29
Recall Awareness	1.93*	.19
Recognition Awareness	.105	.010
Digit Span	.854	.11

Note: $*p < .05$, $**p < .01$.

Results using McKelvie scoring method

Hebb Digits performance for the present experiment was also evaluated using the scoring method advocated by McKelvie (1987). As mentioned previously in this chapter, McKelvie's scoring method, because it is sensitive to fragmentary knowledge of the digit sequences, tends to produce inflated recall scores. The following sections represent instances where using McKelvie's scoring method produced results that differed from the above analyses. Except for these instances, the pattern of results using McKelvie's method matched the analyses above using the proportion of perfectly recalled trials.

Results for comparisons between chunking groups

For the follow-up analyses based on the interaction between series type and chunking, a different pattern of results emerged using the McKelvie scoring method. Specifically, using, a Bonferroni correction, comparison of just the Stimulus Chunking to the No Chunking groups indicated there was no significant interaction between series type and chunking condition was ($F(1,70) = 1.66$, $p > .017$, $MSE = 2.87$, partial $\eta^2 = .023$). In the comparison of the Response Chunked group to the No Chunking group, a statistically significant interaction was observed ($F(1,67) = 7.11$, $p < .017$, $MSE = 15.33$, partial $\eta^2 = .096$; (mean number of digits correctly recalled per trial: No Chunking = 6.53 (repeated), 5.75 (new), Response Chunked = 6.91 (repeated), 4.73 (new), Stimulus Chunked = 7.87 (repeated), 6.42 (new), for a graph of these results, see Appendix C). In summary, these results are in opposition to the results reported earlier in Chapter Two with only response chunking showing clearly increased learning.

Verbal awareness. The only awareness analysis that deviated from the previous pattern of results with data re-scored using the more liberal McKelvie scoring system, were those associated with verbal awareness. A mixed ANOVA of digit series type ("Repeated", "New") by chunking condition ("No Chunking",

"Response Chunked", "Stimulus Chunked") by verbal awareness ("Aware", "Unaware") was again conducted. These analyses indicated a main effect of series type ($F(1,94) = 33.60$, $p < .05$, $MSE = 1.90$, partial $\eta^2 = .263$), with greater recall for repeated series compared to the novel series, showed learning had occurred (mean digit recall score for each trial: Repeated = 7.07, New = 5.69). The results also indicated a significant interaction between series type and verbal awareness (F(1,94) = 4.43, $p < .05$, MSE = 8.45, partial $\eta^2 = .045$). However, unlike in the previous analysis with perfect recall, this time there was also a significant interaction between series type and chunking condition (F(2,94) = 4.55, $p < .05$, MSE = 8.67, partial $\eta^2 = .088$). These results suggest that both verbal awareness of sequence repetition and chunking were accounting for recall performance. However, the interaction between series type, chunking condition and verbal awareness was not significant (F(2,94) < 1, MSE = 1.27, partial $\eta^2 = .014$).

In summary, the use of the McKelvie scoring method while in general agreement with the overall pattern reported earlier, did produce some deviations from the results based on perfectly recalled trials. Specifically, there was no significant recall advantage for the Stimulus Chunking compared to the No Chunking group. Additionally, recall performance for the Response Chunked group was significantly greater than the No Chunking group. Series type was also found to interact with both Verbal Awareness and Chunking.

DISCUSSION

The results of the present experiment were consistent with previous findings (O'Shea & Clegg, in press) indicating a learning advantage for the repeated digit sequence for the Stimulus Chunking compared to the No Chunking group. In addition to replicating O'Shea and Clegg's (in press) earlier findings for the role of perceptual chunking in Hebb Digits learning, the results of the present experiments implicate awareness of sequence repetition as a more important factor in learning than chunking. Specifically, after the effect of awareness was accounted for, there was no further identifiable impact of chunking on Hebb Digits learning. This pattern of results occurred for both Recall and Verbal Awareness (although it was not observed for Recognition Awareness). Interestingly, participants who were classified as unaware, either on the Recall or Verbal Awareness measures, did not demonstrate a significant advantage for recall of the repeated sequence compared to recall of the new sequences. These results then cast some doubt on whether the Hebb Digits task should be regarded as an implicit learning paradigm, given that learning was apparently dependent on the development of awareness of sequence repetition. The present results argue against previous evidence indicating that implicit learning can occur in the Hebb Digits task (McKelvie, 1987). In fact, McKelvie's criterion for classifying participants as unaware was based on responses to a postexperimental questionnaire. As a result, McKelvie's measure may not have been sensitive to the range of conscious knowledge that participants had of sequence repetition (Shanks & St. John, 1994). The use of multiple measures of awareness in the present experiment demonstrated that not all measures have equal sensitivity to the different types of awareness that participants were capable of expressing.

Chunking and Awareness

In addition to supporting a strong role for awareness in Hebb Digits learning, the results of the present experiment found evidence for an interaction between chunking and awareness. Although neither quite reached statistical significance, the chi-square analyses were certainly generally congruent with chunking producing an increase in the number of participants who were aware of sequence repetition when assessed through either recall performance or verbalizable knowledge. Of the three chunking groups, the Response Chunked group had the greatest number of aware participants and fewest unaware participants based on Recall Awareness. For Verbal Awareness, the Stimulus Chunking group emerged with the greatest number of aware and fewest unaware participants. There clearly needs to be further future explanation with a greater number of participants, to determine if the trends observed in the chi-square analyses are meaningful.

In addition to examining the interaction between learning, chunking and awareness in the Hebb Digits task using a composite measure of awareness, a regression analysis was performed with a learning score as a dependent measure and Verbal Awareness, Recall Awareness, Recognition Awareness and Digit Span as the predictor variables. The results of the regression analysis revealed that a unique proportion of variance was accounted for by Recall Awareness ($\underline{r}^2 = .26$) and Recognition Awareness ($\underline{r}^2 = .16$) accounting for 23% (18% adjusted) of unique variance in the learning score. The variables of Recognition Awareness and Digit Span did not significantly predict Hebb Digits learning. The non-significance of Recognition Awareness as a predictor of Hebb Digits learning was consistent with previous analyses which showed that Recognition Awareness did not interact with Hebb Digits learning. The non-significance of Digit Span as a predictor of Hebb Digits learning is somewhat surprising considering that better retention of new digit sequences should lead to greater retention of the repeated digit sequence.

The identification of Recall and Verbal Awareness as significant predictors of Hebb Digits learning suggests that the Hebb Digits task relies on declarative memory in which the contents of memory can be verbally expressed (Squire, 1992). Some theorists have proposed a model of incidental learning in which learning initially occurs in the nondeclarative system and that, transfer of this learning to the declarative system is based on a particular triggering event (Dienes & Perner, 1999, 2002; Frensch et al., 2002). However, the current study offers no evidence that Hebb Digits learning initially begins as a form of nondeclarative knowledge

One interesting question for future research consideration would be to further examine the relationship between Recall and Verbal Awareness. The results indicated only a moderate correlation between Recall and Verbal Awareness, while the regression analysis indicating that both were predictive of some variance in Hebb Digits learning. One possibility is that the learning of the inter-item associations important for the development of Recall Awareness may be a necessary preceding factor for the onset of Verbal Awareness. One way to test this idea would be to assess Hebb Digits task performance under divided attention conditions. As noted by Jacoby and Kelley (1992), divided attention selectively affects recall performance, but not familiarity. If the development of Verbal Awareness follows from Recall Awareness, then the impairment of Recall Awareness through divided attention should produce a similar decrement in the development of familiarity for the repeated digit sequence or Verbal Awareness. However, if Verbal Awareness is a separate form of awareness from Recall Awareness, then performance under divided attention conditions would likely impair Recall Awareness to a greater extent than Verbal Awareness. This latter explanation seems more plausible since the results of the point biserial correlation indicated that Recall and Verbal Awareness were moderately correlated. Still, another possible account of the relationship between Recall and Verbal Awareness is that Recall Awareness may precede and be a necessary condition for the activation of Verbal Awareness. However, once activated Verbal Awareness may contribute independently to the learning process possibly by monitoring which elements of the sequence have yet to be learned.

GENERAL DISCUSSION

The results of the present experiment failed to find support for the hypothesis that chunking processes during perceptual encoding result in a greater degree of learning and awareness of sequence repetition in the Hebb Digits task than chunking processes during responding. Rather, the new data suggest that awareness of the sequence drives improved learning. Matching the notion proposed by O'Shea and Clegg (2005), there was a trend suggesting that chunking, either of the stimuli or the responses, may have served to increase awareness of sequence repetition. But additional study using a greater number of participants is needed to determine whether this trend will reach significance. At present, this data general congruent with the idea that consistency in either encoding processes or response processes boosts awareness for repeated information. The trends observed in the present experiment are also in agreement with previous research suggesting that chunking contributes to the development of awareness for repeated information (Schlaghecken, Stürmer, & Eimer, 2000).

The results of the present experiment by providing strong evidence for the role of awareness in Hebb Digits learning are an important development in our understanding of the mechanisms underlying long-term serial learning. Specifically, learning in the Hebb Digits task appears to rely on the activation of either Recall Awareness or Verbal Awareness or some combination of both of these forms of awareness. In fact, the emergence of either Recall Awareness or Verbal Awareness during task performance appears to facilitate long-term serial learning to a greater extent than chunking processes. These results are in agreement with a number of studies in implicit learning in which it has been found that the development of conscious knowledge of the structure of the task has facilitated learning (Cleeremans & McClelland, 1991; Hartman, Knopman, & Nissen, 1989; Hoffman & Koch, 1998; Perruchet & Amorim, 1992; Willingham, Nissen, & Bullemer, 1989). At present, further studies are needed to determine the relationship between Recall and Verbal Awareness.

The nature of Hebb Digits learning

The results of the present study have also provided some evidence against the view that learning in the Hebb Digits task can occur implicitly or in the absence of conscious awareness of sequence repetition. These results appear contrary to previous findings by McKelvie (1987) and to the general view that Hebb Digits learning can be potentially implicit (Seger, 1994; Stadler, 1993). One explanation for the differences between the present study and McKelvie's work is the more comprehensive assessment of awareness used in the present study. Specifically, the present study assessed three dimensions of awareness of sequence repetition (i.e., Recall, Verbal, and Recognition Awareness), whereas McKelvie used only a verbal assessment of awareness. As a result, McKelvie's unaware group may have consisted of some participants who had recall knowledge of the repeated sequence, but lacked verbal knowledge. Moreover, these participants who had awareness of sequence repetition through recall ability were likely demonstrating significant learning of the repeated sequence compared to the new sequences. Thus, the contamination of McKelvie's unaware group with those participants who possessed recall awareness may have led to the finding that the unaware participants were learning the repeated sequence.

The present findings serve to differentiate the Hebb Digits task from incidental learning tasks such as the SRTT and AG tasks. One characteristic of the Hebb Digits task that may underlie this difference is its greater reliance on the operation of working memory processes than SRTT and AG tasks. For example, in the Hebb Digits task, participants are likely to utilize such working memory devices as conscious rehearsal, inner speech and visual imagery to aid digit retention on each trial. Conversely, in SRTT and AG tasks, these working memory devices may also be utilized, but to a lesser extent. This is consistent with Willingham's (1999) suggestion that implicit learning in the SRTT is based on motoric processes. Furthermore, the opportunity to rehearse the digits prior to responding on each trial in the Hebb Digits task may increase the ability to monitor task performance and develop awareness for sequence repetition. As previously noted, Recall and Verbal Awareness are important to Hebb Digits learning. The development of these forms of awareness may be related to the greater opportunity to monitor task performance.

In contrast, Recognition Awareness, which has been used to classify awareness in a number of incidental learning tasks (Perruchet & Amorim, 1992; Reber, 1967, 1989; Servan-Schreiber & Anderson, 1990; Stadler, 1993), was not found to contribute to Hebb Digits learning. In summary, the reliance of the Hebb Digits task on working memory processes, as well as the evidence against the possibility of implicit learning occurring in the Hebb Digits task, is consistent with the view that conscious processes are integral to the operation of working memory (Baars, 2003; Baars & Franklin, 2003).

Does the lack of evidence for implicit learning in the Hebb Digits task preclude the possibility of using this task in future studies on implicit learning? Not necessarily. If modifications can be made to the Hebb Digits task that can reduce awareness, then the Hebb Digits task should not be discarded as a tool to study implicit learning because it may be valuable in providing a method to investigate the effects of reduced awareness on working memory processes. One way to modify the Hebb Digits task is to decrease exposure to the repeated sequence. This can possibly be done by shortening the number of trials in the typical Hebb Digits task-from 24 to 12-or presenting the repeating sequence less frequently-perhaps on every fourth trial. As mentioned previously, it may be possible to reduce awareness in the Hebb Digits task by adding a divided attention manipulation. An additional method that has been shown to reduce perceptual recognition is to switch stimulus modalities between the study phase and the test phase (Jacoby & Dallas, 1981; Postman & Rosenzweig, 1956). Thus, modifications to the format of the Hebb Digits task may render it a viable tool for assessing implicit learning in a working memory-based task.

A neuroanatomical account of Hebb Digits learning. The results of the present experiment indicate that conscious knowledge of sequence repetition is responsible for Hebb Digits learning. In particular, conscious knowledge in the form of Recall Awareness, or the ability to correctly recall the digits from the repeating sequence, and Verbal Awareness, or the ability to verbally express knowledge of sequence repetition, were found to be the determinants of Hebb Digits learning. Moreover, Recall and Verbal Awareness were found to be only moderately correlated with each other suggesting that these two forms of awareness may be somewhat independent. Within Tulving's (1985) theory linking specific forms of consciousness to the operation of particular memory systems, it appears that Recall Awareness would be associated with semantic memory due to the utilization of processes for strengthening the inter-item connections between digits. Verbal Awareness would be more likely to result from episodic memory processes in which learning is integrated with subjective experience. Thus, the functional differences in the memory systems that give rise to Recall and Verbal Awareness may reflect the operation of different underlying neuroanatomical structures in these forms of Awareness.

O'Reilly and Norman (2002) have developed a model of cortical learning based on differences in the nature of information processing in the hippocampus and the neocortex. Specifically, they consider hippocampal processing to be based on the encoding of details of events, whereas neocortical processing is more generalized and devoted to integrating new information with existing knowledge.

Additionally, hippocampal learning is rapid, whereas neocortical learning is slower and more gradual. O'Reilly and Norman's distinctions between hippocampal and neocortical processing are suggestive of the processing distinctions between Recall and Verbal Awareness. Specifically, Recall Awareness is based on the learning of specific details of the repeated sequence, whereas Verbal Awareness is based on developing knowledge of the task through the monitoring of performance. Thus, Recall Awareness may be based on hippocampal processing and Verbal Awareness may be based on processing in the neocortex.

According to McIntosh et al.'s (2003) findings, the development of awareness in a learning task occurs through interactions between activity in the MTL and the DLPFC. Conversely, unaware participants do not show activity in the DLPFC during learning. McIntosh et al.'s findings that awareness is dependent on activity in the DLPFC is in agreement with earlier work implicating the prefrontal cortex in awareness (Crick & Koch, 1998; Koch & Crick, 1994; Willingham, 1999). Since the hippocampus is a structure located in the MTL, it may be the case that Recall Awareness reflects the processing that occurs in the MTL. Similarly, since the DLPFC is a neocortical structure, Verbal Awareness may reflect the processing occurring in the DLPFC. Awareness of sequence repetition in the Hebb Digits task may, thus, depend on the interaction between Recall and Verbal Awareness. Furthermore, based on findings indicating a role for the MTL as a catalyst in the transition from implicit to explicit knowledge (Moscovitch, 1995), it may be the case that Verbal Awareness is dependent the processing occurring during recall. However, it is difficult to assess whether Verbal Awareness activates Recall Awareness in a top-down fashion or if Recall Awareness activates Verbal Awareness in a bottom-up fashion.

In summary, the results of the present experiment suggest that Hebb Digits learning is mediated by two forms of awareness: Recall and Verbal Awareness. There is also a trend in the data suggesting that chunking may produce an increase in Recall and Verbal Awareness. Although previous work has suggested that implicit learning is possible in the Hebb Digits task (McKelvie, 1987), the present results argue against the possibility of implicit learning occurring in this task. The Hebb Digits task appears to differ from incidental learning tasks in that performance requires a greater contribution from working memory. The reliance of the Hebb Digits task on working memory coupled with evidence against the implicit learning in this paradigm is in line with previous work suggesting that working memory requires conscious processing of information (Baars, 2003; Baars & Franklin, 2003). Finally, the role for Recall and Verbal Awareness in Hebb Digits learning, as well as the potential independence of these systems, may reflect, respectively, contributions from such underlying neuroanatomical systems such as the hippocampus and the prefrontal cortex.

CHAPTER FOUR

CONCLUSION

The capacity to represent serially-ordered information in memory is a fundamental part of everyday life from the retention of word spellings and telephone numbers to the development of skills such as playing the piano and typing. The experiments reported in this dissertation have attempted to account for some of the mechanisms involved in the process by which serially-ordered information acquires a long-term representation in memory. One of the primary cognitive processes utilized in serial learning is chunking or the mental restructuring of a large quantity of information into smaller groups or units. The operation of chunking enables the learner to bypass the limitations of short-term memory in order to retain a greater amount of information (Miller, 1956). In psychology, chunking has been extensively studied in a wide variety of contexts (for a review, see Gobet, Lane, Croker, Cheng, Jones, Oliver, & Pine, 2001) and is an important mechanism in a number of models of short-term memory (e.g., Estes, 1972; Lee & Estes, 1977, 1981; Shiffrin & Cook, 1978). Chunking, however, has been less frequently studied with regard to its effect on the long-term representation of serially-ordered information. In fact, the majority of studies that have examined the long-term effects of chunking are in the domain of implicit learning (Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993; Keele and Jennings, 1992; Koch & Hoffman, 2000; Nissen & Bullemer, 1987; Stadler, 1989, 1993). The format of most implicit learning tasks, such as the SRT, involves the minimal opportunity to rehearse the presented information prior to responding and thus, does not fully engage working memory processes. As a result, the long-term effects of chunking have been primarily studied in tasks that have a minimal working memory requirement.

Chapter Two experimental findings

The experiments reported in Chapter Two investigated the effects of chunking on the long-term representation of serially-ordered information using the Hebb Digits task. The format of the Hebb Digits task not only requires the use of working memory processes, but also enables the separate investigation of the effects of perceptual and motor chunking on serial learning performance. The results of the experiments reported in Chapter Two indicated that learning in the Hebb Digits task is dependent primarily on perceptual rather than motor chunking. Specifically, learning in the Hebb Digits task was found to be significantly greater in the Stimulus Chunking condition, in which the digits were presented in groups of three, compared to a baseline condition or No Chunking condition in which the digits were presented one at a time. In contrast, performance in the Response Chunking condition, in which the digits were presented one at a time and responses were executed in chunks of three, was not significantly greater than the No Chunking condition. The reliance of learning in the Hebb Digits task on the perceptual organization of the stimuli was also evident in the resilience of the Stimulus Chunking condition to the disruption of learning by the requirement to execute responses in random chunks. Although the results of the Chapter Two experiments indicated that perceptual chunking was dominant in Hebb Digits learning, a role for motor chunking was identified based on the observation that learning occurred under conditions where the stimuli were presented in random chunks and responses were executed in chunks of three. Thus, the experiments reported in Chapter Two found that the long-term representation of serially-ordered information in the Hebb Digits task, which is dependent on working memory, is largely mediated by perceptual processes when the stimuli are consistently organized. However, when stimuli are presented in an unorganized fashion, consistency in responding aids in long-term retention.

Perceptual processing account of learning. Based on the experimental results reported in Chapter Two, a theoretical model of learning in the Hebb Digits task can be developed based on the role of perceptual processes in the encoding of the stimuli. This idea appends previous investigations of the Hebb Digits task in which it was found that the consistent coding of stimuli, particularly the initial chunk, strengthened learning of the repeating sequence (Bower & Winzenz, 1969; Schwartz & Bryden, 1971). However, the perceptual processing account of Hebb Digits performance was not in agreement with previous work on the Hebb Digits task in which responding was considered to function as an extra rehearsal opportunity that would enable more elaborative processing to occur (Cunningham et al., 1984). As a result, the perceptual processing account has been expanded to incorporate the view that Hebb Digits learning reflects the operation of a more elaborative form of rehearsal occurring at encoding than at responding. This is consistent with Nairne's (1983) idea that the serial learning of repeated information is strengthened by the more elaborative rehearsal that occurs during encoding than the rehearsal during responding which serves only a maintenance function. Based on this idea that the rehearsal at encoding enables more elaborative associations to occur among the stimuli and thus aid retention, a new series of experiments were planned to test the notion that the elaborative rehearsal that occurs during encoding can increase awareness for the repeated information.

Chapter Three experimental findings

The experiments reported in Chapter Three were designed to test the possibility that perceptual chunking increases awareness for the repeated information which, in turn, leads to enhanced learning. As awareness for sequence repetition was never assessed in the experiments reported in Chapter Two, it was unknown whether the gains in learning observed for perceptual chunking, compared to motor chunking, were due to greater awareness of the repeated sequence. As a result, multiple measures were used to assess awareness under No Chunking, Response Chunked and Stimulus Chunking conditions. These awareness measures assessed three types of awareness that have commonly been studied under incidental learning conditions: Verbal Awareness, Recall Awareness, and Recognition Awareness. Although McKelvie (1987) previously assessed awareness in the Hebb Digits task using an extensive questionnaire format, the experiments reported in Chapter Three represent the first comprehensive assessment of awareness in the Hebb Digits task.

Chunking and awareness. Although the results of the Chapter Three experiments failed to find a significant interaction between chunking and awareness, there was a trend observed in the data suggesting that chunking increases Recall and Verbal Awareness. Although the results of Chapter Three failed to support the hypothesis that perceptual chunking increases awareness, the pattern of findings provides evidence for a role of awareness in Hebb Digits learning. Specifically, Recall and Verbal Awareness appear to mediate Hebb Digits learning. Moreover, after awareness of sequence repetition is accounted for, there is no identifiable impact of chunking on Hebb Digits learning. Thus, in the Hebb Digits task, long-term serial learning is more related to the development of Recall and Verbal Awareness rather than chunking processes.

Recall and Verbal Awareness. Using regression analyses, conducted to identify the significant factors associated with Hebb Digits performance, a significant model emerged in which Hebb Digits learning was significantly correlated with measures of Recall and Verbal Awareness. A correlation found that Recall and Verbal Awareness were only moderately correlated, leaving open the possibility that these forms of awareness may reflect independent underlying forms of conscious knowledge that interact, rather than two different measures of the same underlying awareness. For example, Recall Awareness may reflect the detailed, structural knowledge of the repeating sequence in terms of the inter-item associations that form between the digits. Conversely,Verbal Awareness performance could reflect a more generalized knowledge of the repeating sequence as a whole. Any such functional differences between Recall and Verbal Awareness may reflect, respectively, contributions from such underlying neuroanatomical systems such as the hippocampus and the prefrontal cortex.

Implicit learning in the Hebb Digits task. The results of Chapter Three strongly argue against previous evidence indicating that implicit learning can occur in the Hebb Digits task (McKelvie, 1987). When the learning performance of the aware and unaware participants was separately examined, the results indicated that those classified as unaware on the Verbal Awareness measure, did not demonstrate a significant advantage for recall of the repeated sequence compared to recall of the new sequences. Conversely, the aware participants demonstrated a significant learning advantage for the repeated compared to the new trials. These results suggest that Hebb Digits learning is dependent on the development of awareness of sequence repetition either through recall ability or verbalizable knowledge. Thus, when multiple measures are used to assess awareness the development of conscious knowledge of sequence repetition is a characteristic of performance in the Hebb Digits task. This finding is in agreement with previous research which has suggested that the operation of working memory involves the conscious retrieval of information (Baars, 2003; Baars & Franklin, 2003).

In summary, the perceptual processing account of learning performance in the Hebb Digits task derives support from the findings of Chapter Two in which the perceptual chunking of stimuli rather than the motoric chunking of responses was associated with significant learning. However, the results of the experiments conducted in Chapter Three are not consistent with the view that perceptual processes dominate learning in the Hebb Digits task. However, the perceptual processing account may still be a valid explanation of Hebb Digits learning if further research finds that stimulus chunking contributes more strongly to the development of Recall and Verbal Awareness than the chunking of responses. The findings reported in Chapter Three advance our knowledge of serial learning in the Hebb Digits task for two reasons: 1) awareness of sequence repetition appears to be more important factor than chunking in Hebb Digits learning and 2) Hebb Digits learning may be mediated entirely through explicit processes. Future theoretical accounts of learning in the Hebb Digits task require a more detailed understanding of the interaction between Recall and Verbal Awareness.

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APPENDIX A

QUESTIONS FOR ASSESSING VERBAL AWARENESS

Question 1: Did you notice anything about the task?

Question 2: In the task you just completed, how would you describe the manner in which the digits were presented?

a) Sometimes predictable

b) Always random

Using the options below, enter the number to indicate how confident you are in your response to Question 2.

1____________2____________3____________4____________5

Certain	*Uncertain*

Question 3: Select the option below that best summarizes the task you just completed:

a) A digit sequence was sometimes presented in reverse order

b) Certain number positions were never repeated during the task

c) An entire sequence regularly repeated during the task

d) There was no repetition of any particular digit sequences during the task

Note: Questions used to assess verbalizable knowledge of digit repetition in the Hebb Digits task.

APPENDIX B

QUESTION FOR ASSESSING CONFIDENCE RATING

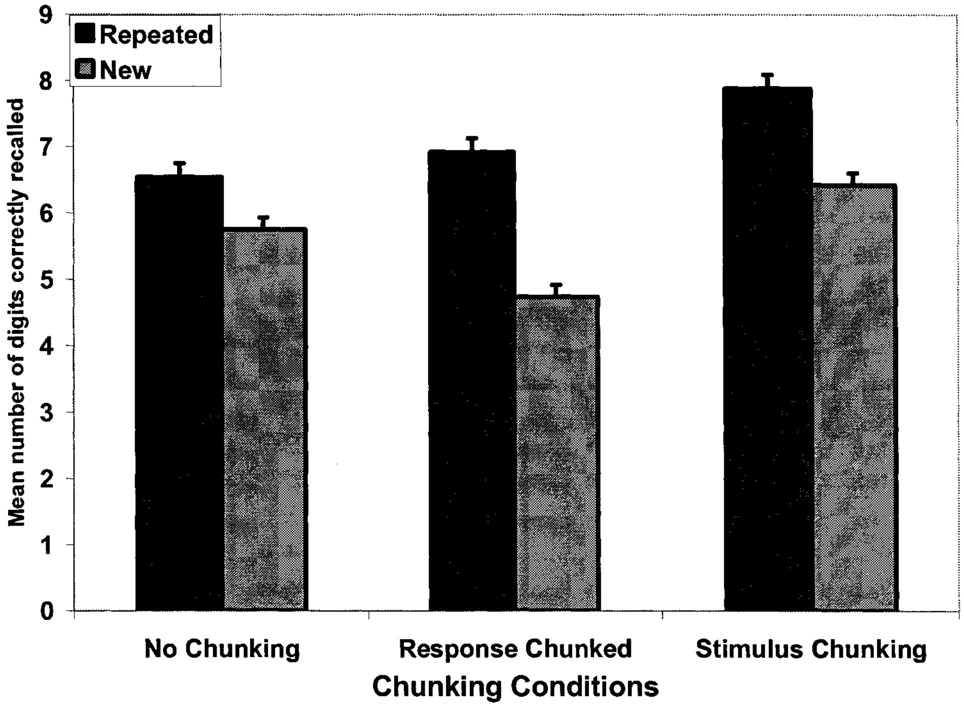
Using the options below, enter the number to indicate how confident you are in your response to each sequence:

1	2	3	4	5
Certain				*Uncertain*

Note: Task used to assess confidence for recognition knowledge of digit repetition in the Hebb Digits task.

APPENDIX C

RECALL PERFORMANCE SCORED WITH McKELVIE'S (1987) METHOD



Recall performance, as scored by McKelvie's (1987) method, for random ("new") versus reoccurring ("repeated") series of digits as a function of chunked condition. The three conditions, based on the structure of the stimuli and responses, are as follows: No Chunking (stimuli presented individually/responses unstructured), Response Chunked (stimuli presented individually/responses executed in chunks of three), Stimulus Chunking (stimuli presented in chunks of three/responses unstructured). (Error bars indicate standard error).