THE REPRESENTATION AND PROCESSING OF ORDER INFORMATION IN MEMORY

by

Michael S. Franklin

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Psychology)
in The University of Michigan
2008

Doctoral Committee:

Professor John Jonides, Co-Chair
Professor Thad A. Polk, Co-Chair
Professor Douglas C. Noll
Associate Professor Luis Hernandez
Assistant Professor Rachael D. Seidler

ACKNOWLEDGMENTS

I would first like to thank my dissertation committee members and my co-chairs for their guidance, support, and advice throughout this process. Specifically, I wish to thank my advisor John Jonides, whose enthusiasm and expertise have served as a model for me to emulate. Special thanks also go to Ed Smith, who started me on this line of research and who has continued to provide helpful advice. Many thanks are also due to the following wonderful research assistants whose hard work made it possible to complete these studies: Marc Berman, Katie Rattray, John Meixner, Courtney Behnke, and Patrick Bisset.

I would like to thank my parents for their incredible support and encouragement throughout my life.

I could not have completed this dissertation without the help of my wife, Tracy, whose sweetness and beauty is only matched by her statistical expertise and editing skills.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
DE	Distance Effect
LTM-CM	Long-Term Memory Checking Mechanism
IFG	Inferior Frontal Gyrus
IPS	Intraparietal Sulcus
MOG	Medial Occipital Gyrus
MTG	Medial Temporal Gyrus
RDE	Reverse Distance Effect
SPL	Superior Parietal Lobule
STG	Superior Temporal Gyrus

CHAPTER 1

General Introduction

The representation and processing of order information is a fundamental aspect of human cognition. At a low level, basic perceptual processes make use of sensory information to create a stable mental representation of the environment that has structure and order. At a higher level, additional cognitive processes such as language also make use of ordered information, in this case patterns of sounds or written text, and allow meaning to be extracted. For example, anyone listening to a foreign language spoken quickly can surely appreciate the higher-order mental processes that allow the native listener to effortlessly make sense of these seemingly random sounds.

Perhaps most central to our conscious lives is memory, which consists of the abilities to encode, store, manipulate, and ultimately retrieve information from the past. The ability to represent and process order information is also an integral part of memory. Specifically, declarative memory has an episodic component largely based on knowing when events happen in relation to one another. There is also a semantic component that not only gives meaning to isolated ‘chunks of knowledge’ but also gives special meaning to sequences of information like numbers and months. The following studies attempt to better characterize various types of order representations in memory as well as the processes involved in accessing this order information.

Study 1: Everyday Routines

Throughout the course of a given day we perform many different actions in many different settings. Our days typically begin with a series of events like showering and getting dressed. During the day we may go to lunch, see a movie, go shopping, and cook dinner. Finally, we may typically end the day with a series of nightly rituals that allow us to relax and fall asleep. The fact that such a vast number of routines can be performed with relative ease suggests a system in place which allows for the efficient organization and retrieval of this information. The goal of the first study was to investigate how order information for some of these everyday routines, like 'going to a restaurant' and 'shopping for groceries', is represented and processed. For example, there are some models in which the actions from a routine are organized according to their specific temporal position within a routine. Other models suggest that position information for the different actions is only coarsely coded such that specific actions are labeled as being in the beginning, middle, or end of a routine. This first study attempts to compare these organizational schemes by examining how variables such as the familiarity of the routine influence performance on a simple ordering task.

Study 2: Numbers and Months

Whereas the first study focused on the organization of temporal information for everyday events, the following studies focus on numbers which can be used to precisely convey ordinal position information. For example, we can use numbers to describe events as occurring first, second, third, etc. However, since numbers are typically thought of in terms of how they convey information about quantity/magnitude (i.e., "how much/how many") there is a gap in the literature concerning the representation and processing of numerical order information. Therefore the goal of this study was to investigate how order processing compares to that of magnitude. Also, since numbers convey order and magnitude information, order processing for months, which do not convey magnitude information, was investigated. A comparison of order processing between numbers and months should help rule out the possibility that results from the order task with numbers are due to automatic processing of numerical magnitude information. Therefore, this study should help inform theories of number representation as well as the representation of order information in general.

Study 3: Neural basis of Order Processing for Numbers

There have been a number of neuroimaging studies which focus on the representation of numerical magnitude information (Ansari et al., 2006a; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Fulbright et al., 2003; Kaufmann et al., 2005; Piazza et al., 2004; Pinel et al., 1999, 2001, 2004; Wood, Nuerk, & Wilmes, 2006). However, there is little work focusing on the neural mechanisms underlying numerical order processing. The work done thus far has been consistent with the idea that there are similar neural mechanisms for magnitude and order processing. However, these studies fail to take into account recent behavioral findings, further substantiated by Study 2, which show that order-related processes can differ from magnitude-related processes. The aim of Study 3 is, therefore, to compare the patterns of brain activation from an order task to those from a magnitude task, each showing distinct behavioral effects. This should allow for the dissociation of participants’ strategies from the neural responses associated with order and magnitude processing.

CHAPTER 2

Distance Effects in Memory for Sequences: Evidence for Estimation and Scanning Processes

Abstract

The current study sought to uncover how temporal information is represented in our knowledge about routine events. In Study 1a we collected norming data on eight routines taken from Galambos (1983). In Study 1b participants were presented with two actions of varying distance from a routine and asked “Are the actions in the correct order?”. We found that a number of variables interact with distance including action position, routine familiarity, and experimental block. These data suggest that sometimes participants are faster when the actions are far apart in the routine, while at other times they are faster when actions are closer together, providing evidence for both distance and reverse-distance effects, respectively. A model is presented to help interpret these data in which temporal information for routine events is both: (1) coarsely coded, and processed by an estimation mechanism, as well as; (2) represented serially, and processed by a scanning mechanism.

Introduction

While our daily experiences lay the foundation for our knowledge of routine events, how that knowledge is represented and accessed is still in question. An important issue with regard to the memory for routine events is the representation of temporal information. When asked to give a description of a routine event, such as going to a restaurant, people are able not only to generate the important actions involved (e.g., ordering from the menu, eating the meal, etc.), but also to specify how the actions relate to one another in time (e.g., ordering the meal occurs before eating the meal). While it is clear that knowledge of the temporal structure of routine events is stored and available for subsequent retrieval, it is not yet clear what the organization and processing of that temporal information is like.

One perspective on the temporal representation of actions within a routine is that information about the position of an action in a sequence is coded by inter-item associations between actions that are temporally adjacent to one another (Ebenholtz, 1963; Young, 1962). Representative actions from a routine would then be organized according to when they take place in the routine with earlier actions connected to later actions (see Figure 2.1a). If one is cued with an early action, the only way to access actions later in the routine is to pass through intermediate ones along the way. It is expected that if memory for routine events is organized by a sequential ordering of the constituent actions, then an action would be easier to access if one has already been exposed to another action that occurs close in time. This could be measured as either a faster response time in judging the temporal relation between two actions that are close to one another in a script, or as some bias toward recalling the actions from scripts in a sequential order.

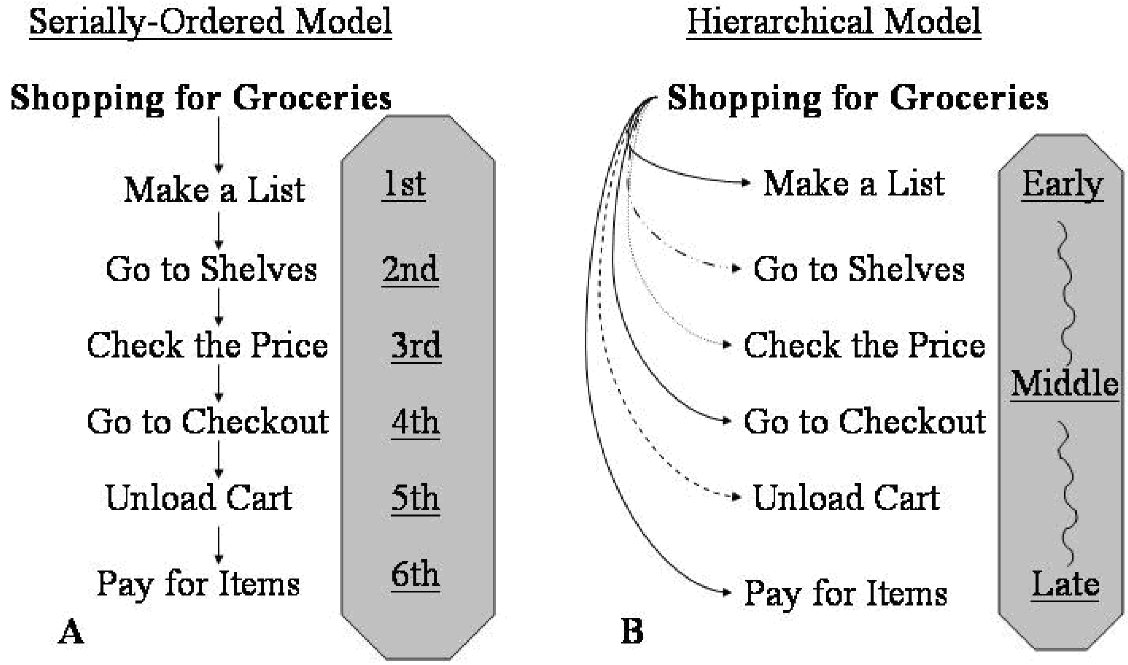


Figure 2.1: Models of routine event memory. This figure compares a hierarchical model with a serially-ordered model of routine memory. In the serially-ordered model (a) actions are organized and accessed according to the order they take place in the routine. Temporal information for actions is coded according to the position of the action in the routine. In the hierarchical model (b), temporal information is coarsely coded. For example, the labels early, middle, and late, could be assigned to the actions, but the actions are not organized or accessed temporally. A darker line would represent stronger connection between the routine and the action.

An alternative hypothesis is that temporal information is only coarsely coded with an action's general position. For example, actions could be classified as taking place early, midway, or later in a routine. Based on this model, coarse temporal codes become assigned to actions from a routine but do not influence the organization of routine memory (i.e., the actions are not necessarily organized sequentially; see Figure 2.1b). According to this model, the actions are organized hierarchically with ones that are most important and/or most frequently encountered in a specific routine being more strongly associated with the routine and easier to access (Rumelhart, 1977; Black and Bower, 1980). If this were the case, then different types of behavioral effects would be expected compared to a model based on inter-item associations. For example, given a task to decide which of two actions occurs earlier in a routine, participants would be faster when the actions occur farther apart from one another. This "distance effect" would be due to the greater discriminability of the temporal codes for pairs of actions farther apart in the sequence (Moyer,1973; Banks, 1977). Also, when asked to generate actions from a routine, participants would tend not to report the actions sequentially. Rather, they would list actions based on some other feature such as centrality, which would be exhibited as a tendency to generate the most important actions from the routine. While these two representational schemes are often pitted against each other, there is evidence that information for routine events is organized both temporally and by properties such as centrality.

Evidence for the hierarchical organization of event memory was provided by Galambos and Rips (1982). In one experiment, participants were asked to decide which of two actions comes either earlier or later in a routine. The distance between the actions was manipulated, such that for the routine of going to a restaurant, *sitting at the table vs. paying the check* would have a greater distance than, *looking at the menu vs. ordering food*. Participants were faster to respond when there was greater distance between the pair of actions; this we call a distance effect (DE). This was interpreted as evidence against a strict serial ordering of the actions in memory. Nottenburg and Shoben (1980) reported the same type of distance effect in an experiment with a similar task and materials. Galambos and Rips (1982) also used a number of other tasks to indicate that centrality, or the importance of an action to a routine, guides the organization of event memory. For example, they showed that participants are faster to identify a single action or a pair of actions as belonging to a specific routine based on centrality rather than on the temporal position of the actions within the sequence.

Despite these findings that support a hierarchical organization of routine memory, some work suggests that actions may be organized in memory by their temporal position in the routine. Haberlandt and Bingham (1984) examined these two models by comparing actions presented in a forward order to those in a backward order. They found that participants were faster to categorize pairs of actions as belonging to a particular routine when presented in the forward order. This indicates that the processing of routines is facilitated when actions are presented in the order in which they take place in the routine, suggesting that a representation may exist that is organized temporally, with a forward ordering of actions in time. Galambos and Rips (1982) did not distinguish between forward and backward pairs in their analyses. It is possible that they might have found different results had they considered the direction of the actions along with distance. Since it may be difficult to scan backwards through a routine, their DE may have been more strongly influenced by the backward pairs than by the forward pairs. Therefore, the distance effect reported may not necessarily be indicative of a general processing strategy across all trial types.

Evidence from Bower, Black, and Turner (1979) and Barsalou and Sewell (1985) also suggest that routines can have multiple organizational schemes and that a serial ordering of actions is one way that these routines are organized. In a series of experiments, Bower et al. (1979) showed that when asked to recall actions from a routine in the order presented, participants tended to recall them in sequential order even if they were presented in a random order. Likewise, Bower et al. found a reverse-distance effect (RDE), in that reading time was faster for pairs of actions from a routine when they were temporally closer. This suggests an organization similar to that shown in Figure 2.1a in which activation spreads between temporally adjacent actions. In an experiment by Barsalou and Sewell (1985), participants were given 20 seconds to generate as many actions as possible from a routine under different instructions. Participants were fastest when the actions were to be generated starting from the beginning and proceeding toward the end, and significantly slower to generate actions based on centrality. This suggests that actions from a routine could be organized temporally, thus facilitating sequential retrieval. An organizational scheme based on centrality would predict that participants are fastest in naming actions according to their importance in the script. Likewise, rather than showing an initial burst when generating items, as is seen when generating category exemplars, participants generated actions at a constant rate. These data provide evidence that participants are likely able to scan through a script one action at a time based on temporal order.

It is possible that the apparently discrepant results reported in the literature could point towards a more general organizing principle for routine memory. Yet little work has been devoted to identifying specific variables that influence the way in which temporal information is retrieved from memory. Some of these variables can be inferred based on work by Foss and Bower (1986) and Franklin and Bower (1988). These two studies used a similar paradigm in which participants had to answer true-false statements about the order of actions from routines. Franklin and Bower (1988) showed that participants were faster when the items were closer together temporally within the routine (a RDE), while Foss and Bower (1986) showed that participants were faster when the items were farther apart within the sequence (a DE). One important difference between these studies (as discussed by Zacks and Tversky, 2001) has to do with the amount of testing done with the material. Franklin and Bower (1988) tested participants repeatedly with the same material, which could serve to facilitate coding of the actions according to their specific temporal position in the routine. Therefore, during testing, participants could utilize this sequential organization and via a scanning procedure be faster for statements closer together in time within the routine. In contrast, the DEs found by Foss and Bower (1986) could then be the result of their participants having only coarsely coded temporal information about the available routines. These results suggest that certain variables, such as familiarity, may influence the type of distance effect. Additionally, different types of distance effects become important when testing between competing theories.

The Present Study

Taken together these studies provide evidence that event memory may be organized by different properties, and as such, multiple strategies may be engaged that utilize these multiple organizational schemes. The present study aimed to identify variables that influence whether memory for routines is: (1) serially-ordered based on inter-item associations and accessed via a scanning mechanism; or (2) hierarchically organized and accessed via an estimation mechanism that processes coarse temporal information. The present studies utilized similar task and materials as Galambos and Rips (1982). An estimation mechanism would be evident by DEs in which participants are faster to make a judgment when the actions are farther apart. A scanning process would be evident through RDEs in which participants are faster for items that are closer together within the sequence.

We were focused on how the following variables interact with distance between actions:

Familiarity- The familiarity of a routine (how familiar participants are with the routines before beginning the experiment) may influence the type of distance effects, so we included routines of high and low familiarity. Specifically, we expected that more specific temporal information would be available for routines of high familiarity which would increase the chance of finding RDEs. In a similar fashion, we expected a DE for routines of low familiarity because only coarsely coded temporal information would be available.

Practice- The results of Franklin and Bower (1988) and Foss and Bower (1986) discussed above suggest that amount of exposure to the test stimuli may influence the type of distance effect. We examined trials from the first half (blocks 1 and 2) and second half (blocks 3 and 4) of the experiment to see if the distance effect changes as a function of participants becoming more familiar with the task and routines included. We expected DEs for the first half of the experiment, and RDEs for the second half as participants become more exposed to the routines and constituent actions.

Stimulus Position-Whether the trial contains an action in the first or last position in the routine (an endpoint item), or contains only middle actions, could influence the type of distance effect. Because coarse temporal information from endpoint actions would likely be sufficient when making an order judgment, we expected trials containing endpoints to show DEs. More fine-grained information would be necessary to discriminate between middle actions, so these items might exhibit RDEs.

Direction- We were interested to see if differences would emerge for actions presented in a forward versus backward order. Actions were presented side by side and those trials in which the earlier action occurs on the left were labeled as forward trials, and trials in which the earlier action occurs on the right as backward trials. Haberlandt and Bingham (1984) indicated an advantage for actions presented in the forward direction. We expected that actions presented in the forward direction would be easier to scan and would produce RDEs, whereas actions presented in the backward direction might lead to DEs. It should be noted that direction can also be thought of as "correctness". All forward trials are in the correct order and vice versa.

Experiment 1 was a run to verify that the routines, constituent actions, and the order of these actions based on the norming study by Galambos (1983) are still applicable to the present college-aged sample. In Experiment 2, we presented participants with two actions from a routine and asked them "Are the items in the correct order?". This instruction varied from the Galambos and Rips (1982) instruction of "Choose the earlier/later action". We decided to probe memory for order with this more general "correct order" instruction, as the latter type of instruction may bias participants towards a more discriminative strategy.

Study 1a

Methods:

Participants

Forty participants were run in this experiment (University of Michigan undergraduates; 26 female, 14 male, mean age = 20.9). Participants were all right-handed and native English speakers. Participants were paid $10.

Stimuli

The Stimuli were taken from Galambos (1983). We chose eight routines each consisting of twelve actions.

Procedure

Using paper and pencil, participants were first presented with the eight routines (as seen in Table 2.1) and asked to rate the familiarity of the routines on a scale from 1 to 10, with 10 being very familiar and 1 not familiar at all. Then for each of the eight routines participants were presented with the twelve actions in a random order and required to place the actions in the correct order by placing a number next to each of the actions. The order of routines was counterbalanced across the participants and each participant saw a different random order of the twelve actions.

Table 2.1. Included are the eight routines used along with familiarity ratings, S.D. and position rating S.D. as collected by Galambos (1982).

HEADER	FAMILIARITY	S.D	Position Rating S.D.
Buying a Car	4.56	2.48	1.31
Going to Movies	9.06	1.43	0.95
Making New Clothes	4.50	3.42	0.63
Pitching a Tent	4.67	2.06	1.01
Playing Some Tennis	4.72	3.46	0.67
Shopping for Groceries	8.94	1.92	0.29
Starting a Car	9.00	1.19	0.86
Writing a Letter	9.06	1.21	1.03

Results and Discussion

In Tables 2.1 and 2.2 we present the mean familiarity ratings and standard deviations for each of the eight routines as reported by Galambos (1983), and the current study, respectively.

Table 2.2. Included are the eight routines used along with familiarity ratings, S.D. and position rating S.D. as collected in Study 1a.

HEADER	FAMILIARITY	S.D	Position Rating S.D.
Buying a Car	3.60	2.60	1.37
Going to Movies	8.44	0.88	0.88
Making New Clothes	2.49	2.52	0.96
Pitching a Tent	3.30	2.70	1.47
Playing Some Tennis	5.11	2.92	1.05
Shopping for Groceries	8.37	0.91	0.57
Starting a Car	8.21	1.61	1.48
Writing a Letter	6.78	2.33	1.33

Also included in the table is the average standard deviation associated with participants’ position ratings for the twelve actions for each of the eight routines. A higher number means that there was greater discrepancy in participants’ ratings of the order of the actions for the given routine. Table 2.3 presents the average position ratings and standard deviations for each of the actions for the eight routines.

Table 2.3. For each of the eight routines, included are the twelve actions and the mean position ratings and S.D. as collected by Galambos (1983) and in Study 1a.

	Experiment 1a Sequence		*Galambos (1983) Sequence*	
	Mean	S.D	Mean	S.D
Making New Clothes				
Select the Pattern	1.46	0.87	1.19	0.75
Buy the Material	1.98	0.52	1.94	0.25
Buy the Thread	2.66	0.85	2.94	0.25
Lay out Fabric	4.27	0.67	4.00	0.37
Pin on Fabric	6.46	1.55	5.50	0.63
Cut the Material	5.22	1.01	5.50	0.63
Thread the Needle	6.51	0.87	7.06	0.57
Sew Pieces Together	7.88	0.68	8.13	0.50
Try on Garment	10.95	1.16	9.69	1.08
Put Buttons on	9.56	0.87	9.88	1.03
Adjust the Hems	9.95	1.22	10.37	0.96
Iron the Garment	11.10	1.22	11.81	0.54
Shopping for Groceries				
Make a List	1.00	0.00	1.00	0.00
Enter the Store	2.09	0.30	2.00	0.00
Get a Cart	2.90	0.30	3.00	0.00
Go to Shelves	4.00	0.00	4.00	0.00
Reach for Items	5.46	0.50	5.31	0.48
Check the Price	5.58	0.77	5.94	1.18
Load the Cart	7.34	1.25	6.94	0.25
Go to Checkout	8.07	0.51	8.06	0.44
Pick Shortest Line	8.804	0.40	8.81	0.40
Unload the Cart	10.39	0.77	9.94	0.25
Pay for Items	10.97	0.79	11.06	0.25
Load up Bag	11.29	1.28	11.94	0.25
Playing Some Tennis				
Reserve a Court	1.61	0.89	1.38	0.62
Get the Equipment	1.68	0.61	1.69	0.48
Go to Courts	3.05	1.24	2.94	0.25
Choose a Side	4.24	0.83	4.06	0.25
Warm up Volley	4.98	0.57	5.19	1.05
Start a Game	6.05	0.92	6.00	0.37
Serve the Ball	7.34	1.09	7.13	0.34
Run for Shot	8.68	0.88	8.56	0.89
Make the Return	9.15	0.99	8.81	0.54
Keep the Score	9.85	1.33	9.94	1.44
Retrieve the Balls	9.73	2.42	10.50	1.41
Congratulate the Opponent	11.68	0.88	11.81	0.40

		Starting a Car		
Unlock the Door	1.10	0.30	1.06	0.25
Open the Door	2.20	1.12	1.94	0.25
Get into Auto	3.80	2.32	3.00	0.00
Adjust the Seat	4.80	1.35	4.13	0.50
Lock Seat Belts	5.95	1.50	5.37	0.62
Key in Ignition	5.61	1.55	6.44	1.03
Check the Mirrors	7.05	2.06	7.19	1.97
Shift into Neutral	8.66	1.09	8.06	1.61
Turn the Key	6.93	1.25	8.63	0.81
Check the Traffic	10.24	2.33	10.81	0.75
Depress the Accelerator	10.95	1.99	10.37	1.63
Shift into Drive	10.27	0.98	11.00	0.89
		Going to Movies		
Check the Newspaper	1.27	0.63	1.31	0.70
Pick a Show	1.85	0.48	2.13	0.34
Find out time	2.98	0.35	3.25	0.45
Go to Theater	4.20	0.64	4.38	0.62
Stand in Line	5.95	1.18	5.37	0.72
Buy the Tickets	6.32	0.91	6.38	0.72
Enter the Theater	6.49	1.72	7.31	1.25
Give Usher Tickets	8.49	0.78	8.00	0.73
Watch the Previews	10.51	1.86	8.50	4.34
Buy Some Popcorn	8.02	0.96	9.38	0.96
Find a Seat	9.88	0.87	10.00	0.63
Leave the Theater	11.98	0.16	12.00	0.00
		Writing a Letter		
Get some Paper	1.02	0.16	1.13	0.34
Put on Date	3.02	1.60	2.63	1.09
Put on Salutation	3.88	2.14	3.31	0.70
Compose the Message	3.66	0.73	3.69	1.01
Sign Your Name	5.05	0.71	5.31	0.60
Put on Postscript	7.61	2.71	6.25	1.65
Get an Envelope	6.05	2.25	6.25	2.32
Fold the Paper	7.29	1.31	8.13	0.89
Address the Envelope	9.49	1.33	9.31	1.40
Put Into Envelope	8.78	1.08	9.63	0.72
Seal the Envelope	10.34	1.04	10.81	0.75
Put on Stamp	11.49	0.98	11.56	0.89
		Pitching a Tent		
Find Good Location	1.02	0.16	1.00	0.00
Prepare the Site	2.32	1.59	2.00	0.00
Unpack the Canvas	3.44	1.03	3.33	0.72
Get the Stakes	5.34	2.10	4.93	1.16
Unfold the Canvas	4.95	1.58	5.67	1.54
Get out Ropes	6.34	1.89	5.67	1.59
Pound Stakes in	7.41	1.97	7.07	1.83
Put up Poles	6.93	1.40	7.07	1.71

Raise the Top	9.02	1.64	8.93	1.03
Tighten the Ropes	9.51	1.29	9.67	0.98
Check for Stability	10.88	1.72	11.07	0.70
Tie Back Flap	10.76	1.32	11.60	0.83
		Buying a Car		
Look at Advertisements	1.24	0.43	1.06	0.25
Select the Model	2.32	0.82	2.44	1.03
Look at Engine	4.15	1.57	3.25	0.45
Take Test Drive	3.95	1.00	4.13	0.72
Bargain About Price	5.59	0.92	5.31	0.60
Arrange the Financing	5.80	1.66	6.56	1.67
Sign Sales Contract	7.83	1.07	7.75	1.48
Get Temporary License	7.39	3.51	8.63	3.12
Pay the Money	9.12	1.40	9.06	1.39
Get Title Transferred	9.02	1.49	9.13	1.45
Get the Keys	9.76	2.07	9.13	2.71
Drive it Home	11.85	0.48	11.56	0.89

A comparison of our norming data with those of Galambos (1983) (see Tables 2.1 and 2.2) indicates no significant difference for either familiarity ratings (t(7) = 0.88, p = .41, two-tailed) or the average standard deviation of position rating (t(7) = 2.00, p = .09, two-tailed). While there is a trend indicating that our participants have a slightly more difficult time putting the actions from these eight routines in correct order, overall this difference is not statistically different. Likewise participants' familiarity ratings did not significantly differ from Galambos (1983). Therefore we proceeded with Study 1b knowing that participants are able to place the actions from the eight routines into the correct order and that the familiarity of the routines from Galambos (1983) are similarly rated by our sample of college-aged participants.

Study 1b

Methods:

Participants

Twenty-two participants were tested in this experiment (University of Michigan undergraduates; 8 male, 14 female, mean age = 20.2). Participants were all right-handed and native English speakers. Participants were paid $10.

Stimuli

The stimuli were taken from a study by Galambos (1983) which collected norms for everyday activities. We used 8 routines, picking 4 of high familiarity (mean familiarity = 7.95, S.D. = .78) and 4 of low familiarity (mean familiarity = 3.62, S.D. = 1.09); see Table 1 for a list of routines used). Each of the routines consisted of 12 actions. In the study by Galmbos and Rips (1982) three distances of 2, 5, and 8 were used. We used an equal number of action pairs that were either 4 or 7 steps apart. Since it was only possible to have five of the seven step pairs, our stimulus-set was limited to ten unique pairs of actions from each of the eight routines yielding a total of 80 trials. The direction of the actions was counterbalanced across participants such that half of the participants saw the same pair of actions, but on the opposite side of the screen. Twenty practice trials were taken from five additional routines (washing your hair, sending a gift, brewing some tea, throwing a party, and taking a photograph). Two four-step, and two seven-step actions were chosen from each of these routines.

Procedure

E-Prime experimental software (Psychology Software Tools, Inc.) was used for stimulus presentation and for recording behavioral data on Dell PC. The stimuli were presented in black with a white background in Arial, size 24 font. Participants were seated 60 cm from the monitor. The sequence of events on a trial was as follows: Participants were presented with a fixation point for 1500 ms. The name of the routine then appeared on the screen for 1000 ms followed by the two actions from the routine until a response was detected. The actions were presented side by side. Participants were instructed to press the ‘1’ key with their left hand if the items were in the correct order, meaning that the item on the left preceded the item on the right within the routine, and the ‘0’ key with their right hand if they were in the incorrect order. For example, given the header *Going to a Restaurant*, two actions could be *Read the Menu* on the left and *Tip the Waiter* on the right. In this case the participant would respond “correct.” Participants were instructed to respond as quickly as possible while maintaining a high level of accuracy. Before the experimental trials began participants went through 20 trials of practice to assure that they understood the task. The experiment was divided into 4 blocks of 20 trials with a rest in between blocks.

Results and Discussion

Data were trimmed on an individual-participant basis for trials that exceeded 1.5 times the interquartile range. This resulted in a loss of 4.3% of the data. Only correct trials were analyzed. Table 2.4 displays mean reaction time and accuracy for each of the variables of interest: distance, familiarity, direction, position, block.

Table 2.4. Included are the mean reaction time (in milliseconds), S.D., and accuracy for each of the variables of interest.

		RT	S.D.	ACCURACY
Distance	Four	1900	252	0.842
	Seven	1905	482	0.892
Familiarity	High	1858	473	0.876
	Low	1947	530	0.858
Direction	Forward	1864	490	0.824
	Backward	1951	496	0.920
Block	First Half	1872	508	0.859
	Second Half	1933	497	0.875
Position	Middle	1909	502	0.857
	Endpoints	1889	515	0.883

Accuracy Data

While we have included accuracy data in the table, we were primarily interested in reaction times since the speed of processing should be more informative regarding distance effects. Therefore we performed analyses for reaction times only. Since it appeared as though a possible speed-accuracy trade-off might have been occurring for the distance variable (overall participants were faster in the four-step compared to seven-step trials, but more accurate in the seven-step compared to four-step trials) the correlation between errors and reaction times was analyzed, producing a slightly positive correlation ($r = .13$, $p = .01$). This indicates that participants were slower on error trials and not trading speed for accuracy.

Reaction Time Data

Main Effects

There was no significant main effect of the distance manipulation ($F(1, 21) = .443$, $p = .519$). Overall participants were only slightly faster (by 5 ms) when the actions were closer together. There was a main effect of familiarity ($F(1, 21) = 5.483$, $p = .029$), with the mean reaction time 89 ms faster for actions that were taken from more familiar routines. There was no significant difference in reaction time to pairs of actions that contained endpoint items vs. middle items ($F(1, 21) = .454$, $p = .509$). There was a main effect of direction ($F(1, 21) = 5.483$, $p < .001$), with the mean reaction time 90 ms faster for actions that were in the forward direction (i.e., the correct order). There was no significant effect of block ($F(1, 21) = 2.138$, $p = .159$).

Interactions

Position x Distance: There was a significant two-way interaction between position and distance, (F(1, 21) = 10.635, p = .004; see Figure 2.2). For trials containing middle items participants were faster when the actions were closer together (F(1, 21) =3.825, p=.064), showing a marginally significant RDEs. For trials with endpoint items, participants were faster when actions were farther apart, (F(1, 21) =7.055, p=.015), showing DEs.

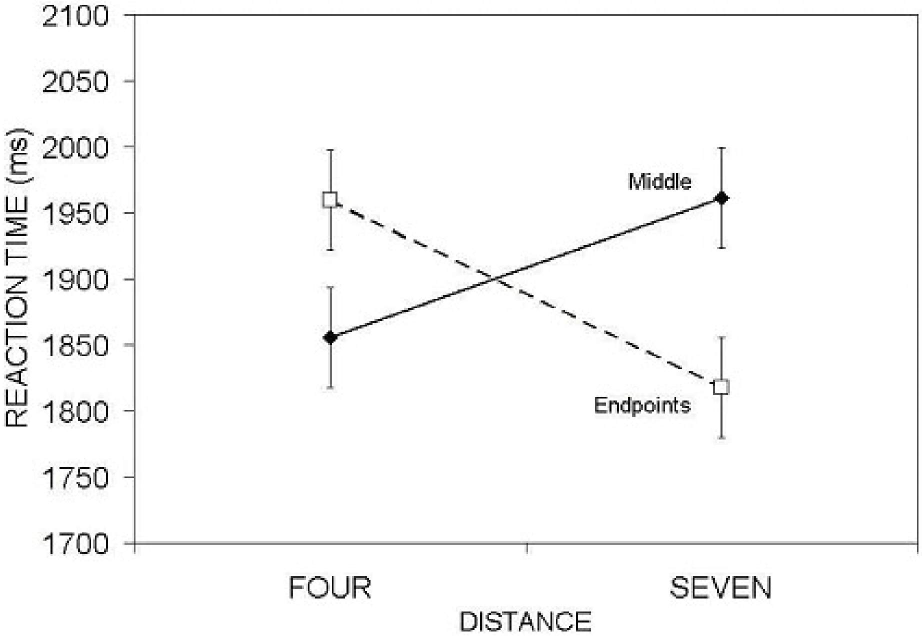


Figure 2.2 : Interaction of position and distance. Error bars displayed are 1 S.E.

Familiarity x Distance: Likewise there was a significant interaction between familiarity and distance, (F(1, 21) = 12.6, p = .002, see Figure 2.3). RDEs were seen for routines of high familiarity, (F(1, 21) =7.089, p = .015), and DEs were seen for those routines of low familiarity, (F(1, 21) =5.558, p=.028).

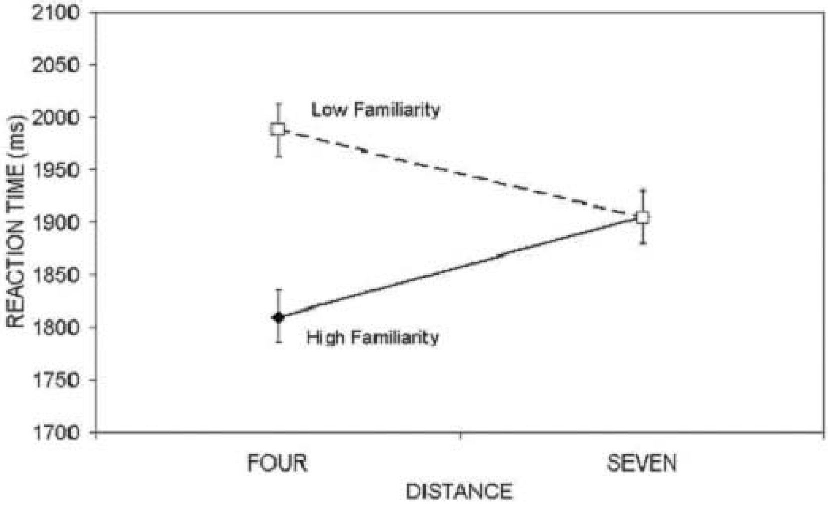


Figure 2.3: Interaction of familiarity and distance. Error bars displayed are 1 S.E.

Block x Distance: There was an interaction between block and distance (F(1, 21) = 8.975 p = .007; see Figure 2.4), with participants showing a trend toward RDEs in the second half (F(1, 21) = 3.568, p = .073), and showing a DE for the first half (F(1, 21) = 5.512, p = .029).

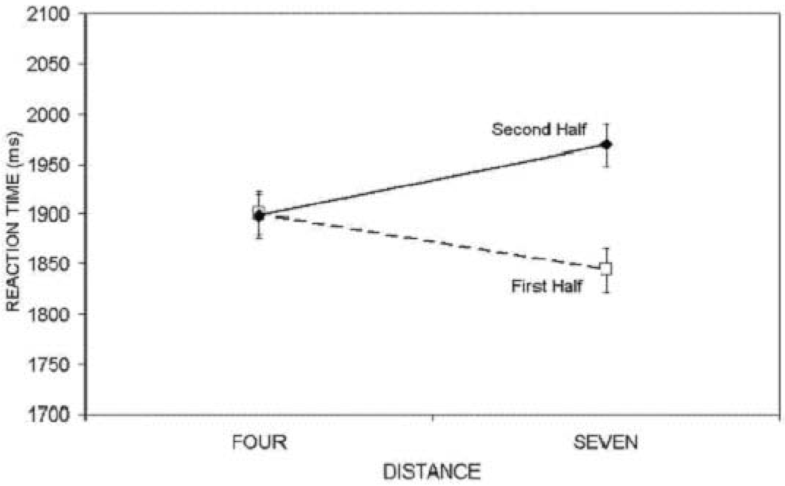


Figure 2.4: Interaction of block and distance. Error bars displayed are 1 S.E.

Direction x Distance: There was only a trend toward an interaction between direction and distance (F(1, 21) = 2.618, p = .121). This implies no significant relation between the actions being in a forward or backward order and the distance effects seen.

The present results failed to find an overall distance effect like that reported by Galambos and Rips (1982). Rather, the results of the present experiment suggest that distance effects are contingent on a number of variables. First, whether a trial contained an endpoint or not had an effect on the type of distance effect. When participants encountered an endpoint item they were faster when the other action was farther away within the routine (a DE). This implicates an estimation strategy for trials with endpoint items rather than a serial search through the routine. In contrast, for middle items, participants were faster when the actions were closer together temporally in the routine (a RDE), which implicates a scanning strategy. These distance effects were also influenced by the block of the experiment. Participants showed DEs for the first half of the experiment and RDEs for the second half of the experiment. The distance by familiarity interaction demonstrates that participants are estimating for low familiarity routines and scanning for high familiarity routines. While the difference between our “correct order” instruction and Galambos and Rips’ (1982) “choose the earlier/later action” instruction may account for some of the differences between our results, it is possible that had Galambos and Rips (1982) investigated the same variables as in the present study (i.e., stimulus position, routine familiarity, and experiment block) similar interactions with distance may have emerged.

These results support the notion that it is possible to obtain RDEs. This suggests that besides the coarse coding of temporal information, memory for everyday routines is also represented serially according to inter-item associations, and that participants are able to scan through this representation.

General Discussion

Nottenburg and Shoben (1980) and Galambos and Rips (1982) showed that DEs occur in sequencing tasks of routine memory. These DEs have been taken as support for a hierarchical model of routine memory (see Figure 2.1b). The results of the present experiments differ from these studies in finding evidence that participants sometimes find it easier to compare actions that are closer together within the routine. This RDE implies a serial search or scanning mechanism in addition to an estimation mechanism likely responsible for the DEs. The variables that influence the type of distance effects are position, familiarity, and experimental block.

These findings have a number of implications for how memory for everyday routines is organized, as well as how that information is accessed when participants make decisions about the order of actions in a routine. Figure 2.1a provides one framework for describing this organization. Under this model, routines are represented as a set of actions that are organized sequentially starting from the beginning of the routines. This model would explain the RDEs because actions that are close to one another should be easier to access. However, this model alone cannot account for both scanning and estimation effects. The implication of the DE is that events from a routine are not simply coded by inter-item association. There must be some additional types of temporal codes that allow for a faster comparison when there is greater temporal distance and hence greater discriminability between actions.

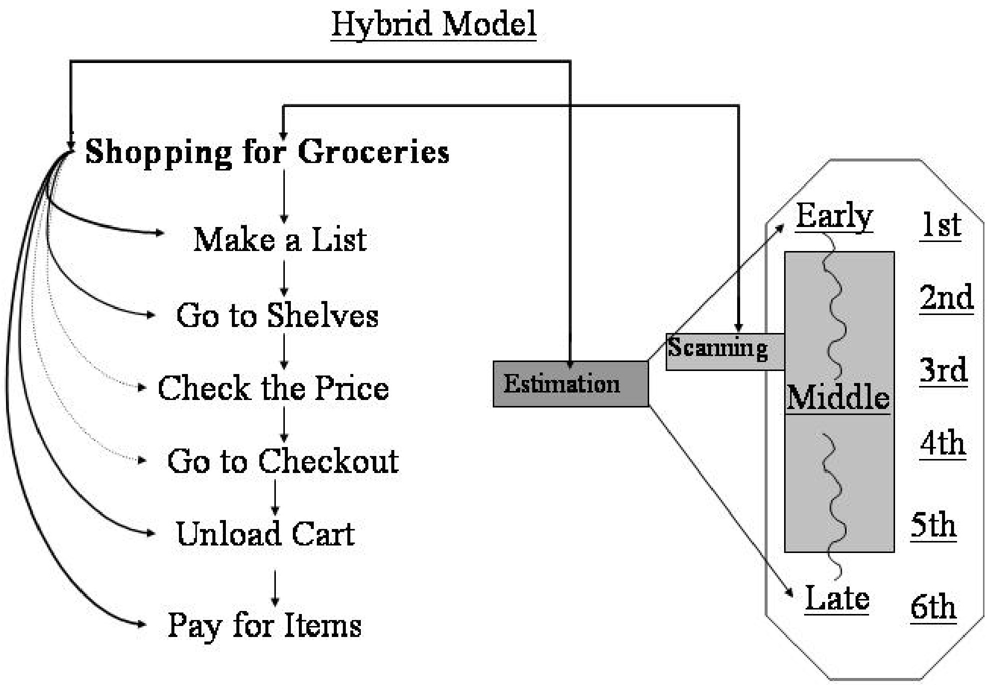


Figure 2.5: A hybrid model of routine memory. According to this model, temporal information is coded both by position and by coarse codes. Scanning occurs for middle items and for highly familiar routines and makes use of positional information. Estimation occurs for endpoint items and less familiar routines using coarse codes

Figure 2.5 shows a hybrid of the hierarchical and serial ordered models of routine memory that could help explain the results of the present experiments. According to this model, temporal information from routines is represented both hierarchically and serially. The hierarchical representation consists of temporal codes that are initially coarse and become more specific at lower levels. When participants have sufficient information to make the comparison (i.e., each of the actions has a distinct code), a decision is made. This explains why participants are sometimes faster when actions are farther apart. Accessing more fine-grained temporal information takes time because that information is available only at lower levels. Information about routines can also be coded such that each action is uniquely coded by its temporal relation to other adjacent items in the routine. This information is accessed through a scanning mechanism that goes through the actions serially from early to later. Under this mechanism participants would be faster when actions are closer together in time.

Together, the results from this study support the assumption that there are multiple organizational schemes and mechanisms for accessing temporal information. One effect that supports this assumption is the significant interaction of position by distance. This interaction implies that participants are scanning for the trials with only middle actions and estimating for trials containing endpoint actions. This suggests that on all trials, participants are making use of coarse temporal information. The endpoint actions are distinctly tagged as beginning or end items and have a special status. When an endpoint action is encountered, participants use an estimation mechanism and are facilitated by the greater discriminability between distant actions.

In trials with middle actions, the actions are all coded as “middle items”, and thus there would be no benefit from using this coarse-coded information. Assuming that more fine-grained temporal position information is available for the routine, a scanning mechanism could be engaged starting from the first action presented. Since we found similar DEs for backward trials, it is plausible that participants must first locate the earlier item and then scan forward, which would take longer on backward trials.

The two other variables that interact with distance, familiarity and block, can also be understood in the context of the proposed model. Because participants see only 10 trials taken from each of the 8 routines, it is likely that over the course of the experiment, specific position information becomes more available. As Zacks and Tversky (2001) suggest, greater practice with the routine could result in scanning through the routine. This would explain why in the second half of the experiment participants are more likely to use a scanning strategy. The interaction of distance and familiarity could be due to the fact that routines with which participants are more familiar before beginning the experiment are more likely to be represented by specific position information. The low familiarity routines are more likely to be coarsely coded.

This hybrid model is similar to the representation of scripts discussed by Abbott, Black, and Smith (1985). Based on participants’ inferences while reading descriptions of various routine events, Abbot et al. (1985) developed a model in which everyday routines are represented both hierarchically and serially. In their model each routine is organized hierarchically in that there is a representation of the routine name (e.g., going to a restaurant), various scene headers (e.g., enter, order, etc.), as well as the actions within these scenes (e.g., open door, go to table, sit down). In addition to this hierarchical arrangement, each of the scene headers and actions within the scenes are connected serially. Since the various scene headers take place at discrete times in the routine, these likely have distinct coarse codes, i.e., early, middle, and late. This would lead to different predictions when comparing our hybrid model and the model of Abbott et al. (1985). Their model predicts RDEs when comparing scene headers, since the scene headers are proposed to be organized serially, whereas our data suggest that scene headers have distinct coarse codes and therefore would be processed by an estimation mechanism yielding DEs.

These distance effects also rule out the possibility that a single process (scanning) takes place within a hierarchical representation as is the case in the hierarchical editor model discussed by Rosenbaum et al. (1984) concerning movement sequences. If this model were applied to routine memory then subjects should be faster comparing scene headers that are closer together in time, which does not seem to be the case. The differences between the models developed for movement sequences and the current model of routine memory may be due to the fact that information for routines is stored in long-term memory, while complex movement sequences are thought to be uniquely generated each time based on past movements and presently competing movements. In order to investigate the relation between these models in more detail it would be necessary to generate stimulus materials whose structure better controls for the number of scenes (goals) and constituent actions within scenes (subgoals), and tests a more extensive range of distances.

Though not much recent work has been done studying memory for routines, a current study by Dean et al. (2005) investigated mental representations underlying judgments of symbolic distance tasks of the sort studied by Moyer and Landauer (1967). This study provides further evidence that commonly found DEs across a range of comparison-types need not require the generation of an image, since the DEs remained intact after selective spatial and visual interference. The present work is consistent with these findings in that it is unlikely that our DEs are due to participants using an image of the actions within the routine. On the other hand, the RDEs may reflect a type of mental simulation of actions from a routine. This is consistent with current work on the topic of mental simulation which suggests that understanding a description of an action involves a mental simulation of the action (Goldman, 2002; Hesslow, 2002).

Other research in the domain of number processing also relates to the present study. For example, work by Dehaene et al. (1990) suggest that number comparison takes place by holistic processing of numbers on an analogue number line. This is applicable to the present study in which DEs emerge from an estimation mechanism working with coarsely coded information. It is not yet clear if there is an analogue to the RDEs seen in the present experiment, though a recent study by Turconi et al. (2006) suggests that different distance effects can be obtained in a number comparison task depending on whether the instruction focuses on order or magnitude.

While our study describes aspects of memory for routines *across* routines as a whole, much of the current work in this domain focuses on a finer level discrimination *within* routines by studying event structure perception (e.g., see Zacks, Tversky, and Iyer, 2001). This line of research by Zacks and colleagues (2001) suggests that routine events are organized hierarchically, similar to the model proposed and Abbot et al. (1985) discussed previously. By analyzing routines from this perspective, the work on event structure makes contact with a number of domains including language processing, memory, planning, and action; all of which are thought to share a similar hierarchical structure (Zacks & Tversky, 2001). While we find evidence for different coding and retrieval processes across routines as a whole, the results do not directly offer insight into the above hierarchical models. This is largely due to the fact that the stimuli used in the present study (from Galambos & Rips, 1982) were constructed to look at distance across entire routines, not taking into account the lower level event structure suggested by the hierarchical models.

Even though our study does not provide information about the sub-structure of routines, the present work contributes to our gross knowledge of memory for routines and could inform research on the representation and processing of order information in memory. For example, in the domain of working memory, Marsheutz et al, (2000, 2005, 2006) have studied how order information is represented. In their task participants were shown 5 letters vertically on the screen for a brief period of time, followed by a delay, then were probed with two of the letters. Participants were required to decide if the letters were in the correct order or not. Results revealed DEs, such that participants were faster to make a decision when the letters were farther apart in the sequence. Since we also know that participants can scan through information in working memory, as evidenced by performance on forward and backward span tasks (for a review see Lewandowsky & Li, 1994), we now have evidence for both DEs and RDEs in tasks that tap working memory for order information. It is possible that some of the variables discussed in this paper including familiarity, practice, and the occurrence of endpoint items could also play a role in the type of strategy participants use in these working memory tasks.

In addition, previous research has demonstrated that frontal patients have a deficit in sequencing information. For instance, given an everyday routine such as ‘going to a restaurant’ frontal patients can name numerous actions that take place in the routine, but have difficulty arranging the items in the correct temporal sequence (Sirigu et al., 1995). The present results dissociating DEs and RDEs in order judgments could be useful in understanding the specific nature of this deficit as well as the neural mechanisms of order processing in healthy populations. While a number of neuroimaging studies in different domains (Dehaene et al., 2003; Marshuetz et al., 2000; Pinel et al., 1999, 2001, 2004) suggest DEs are mediated by parietal cortex, there are no comparable brain imaging data for RDEs. This is probably largely due to the scarcity of these effects in the literature. The significant RDEs from the present study make the task and manipulations used here a good candidate for investigating these aspects of order memory.

Conclusions

By finding evidence for DEs and RDEs, the present study supports the idea that temporal information for routines is represented both serially, coded by inter-item associations, and hierarchically, based on coarse temporal codes. We have shown that participants tend to scan through the serial ordered representation for trials with middle items, for highly familiar routines, and for the second half of the experiment. An estimation mechanism makes use of the coarse codes and was seen for trials with endpoint items, for less familiar routines, and for the first half of the experiment.

CHAPTER 3

Processing of Order Information for Numbers and Months

Abstract

Despite a great deal of research on the processing of numerical magnitude, few studies have investigated how magnitude relates to information about the order of numbers. The present study attempted to investigate order-related processing for numbers as well as months of the year to see whether processing of order information differs from magnitude information. Whereas number-comparison tasks typically reveal distance effects (comparisons are easier the greater the distance between two numbers), the present results reveal a different pattern. These data suggest that a scanning mechanism is engaged when information crosses a boundary (i.e., when numbers cross a decade or months cross the year boundary), whereas information at a given level (i.e., within a decade for numbers and within the January-December calendar year for months) can be accessed via long term memory irrespective of distance.

Introduction

Processing numbers is fundamental to cognition. We can all count, estimate magnitudes, do simple arithmetic and otherwise manipulate numbers. Contrariwise, a breakdown in number processing due to brain lesions can lead to significant deficits in activities of daily life (Rosselli et al., 2006; Osmon et al., 2006; Shalev et al., 2005; Geary, 1993). Indeed, processing quantity is so fundamental a cognitive skill that a basic sense of number is present in infants, other primates, and other species (Brannon, 2002; Brannon & Terrace, 1998; Dehaene, Dehaene-Lambertz, & Cohen, 1998).

While debate continues over subtleties of specific models, numbers are generally thought to be represented along an analog internal number line with decreasing distance between numbers as magnitude increases, or with increasing variability in the representation of number position as magnitude increases (Dehaene, 2003; Dehaene & Changeux, 1993; Gallistel & Gelman, 2000; Wynn, 1998; Whalen et al., 1999). Two pervasive behavioral effects have been instrumental in shaping these models, the distance and size effects. The distance effect (DE) refers to the fact that comparison of the magnitude of two numbers is accomplished more quickly and with greater accuracy when they span a greater distance (Moyer & Landauer, 1967). The size effect is revealed in longer reaction times to compare numbers of greater magnitude (Parkman, 1971; Ashcraft, 1992)

The tasks that have led to these models of number representation almost exclusively assess the stimuli solely on the basis of their magnitude. These tasks are often collectively referred to as magnitude comparison tasks, and typically involve asking participants to pick out the smaller or larger of two numbers, or to decide whether a given number is smaller or larger than some target number. However, in addition to information about magnitude, it is important to note that numbers also represent information about order. For example, the number ‘3’ can be used to describe a specific quantity, or magnitude (i.e., “There are *three* apples on the table”), as well as the order of an item in a list (“The runner finished in *third* place”). While the magnitude comparison tasks described above clearly require the use of information about magnitude, it is less clear whether adequate tasks have been designed to assess numbers in terms of their ordinal properties.

Past studies that have attempted to assess information about order for numbers often rely heavily on magnitude information. For example, in one type of order task, participants were required to order arrays of stimuli based on the number of stimuli present on the screen (Brannon & Van De Wal, 2001; Brannon, 2002; Cantlon & Brannon, 2006). Clearly magnitude information comes into play in these experiments in that, for example, an array with five squares contains a greater quantity of items than an array containing two squares. Turconi and colleagues (2006) also tried to assess order processing by having participants decide whether two numbers were in the correct order. Performance on this task was compared to the more standard magnitude comparison task of choosing the larger, or smaller, of the two numbers. This work, however, also seems problematic since a strategy based on magnitude information can lead to the same result as that of order. For example, deciding if two numbers are in the correct order can be done by seeing if the largest number is to the right, or the smallest number is to the left, focusing on magnitude instead of order information. As such, the current way of thinking about number processing may be incomplete by either only focusing on magnitude information or by using order tasks that heavily rely on the use of magnitude information.

The lack of adequate order tasks is particularly relevant to theories of number processing given recent evidence that order processing may differ from magnitude processing. For example Turconi and colleagues (2006) provide evidence for an order specific process in a number comparison task. When participants were shown two numbers and asked the question, “Are the numbers in the correct order?”, they showed RDEs if the small-distance numbers were adjacent and ascending (e.g., 6_7 is faster than 4_7) and DEs for all descending pair comparisons; however, when they had to choose the larger or smaller of two numbers, they showed DEs regardless of adjacency or whether the numbers were ascending or descending. The RDE suggests a scanning mechanism that accesses each number serially, taking longer when they span a greater distance. Alternatively, the possibility of greater familiarity for ascending adjacent pairs raises the possibility that the RDE is simply due to easier retrieval of these trial-types. Either way, the processes utilized with the order instruction differed from the DEs associated with magnitude comparison tasks.

Study 1 also suggests that there is distinct order-related processing for them (Franklin, Smith, & Jonides, 2007). In this study, participants were required to assess the order of two actions from an everyday routine. Whereas comparison tasks in this domain typically have shown DEs (Galambos & Rips, 1982; Nottenburg & Shoben, 1980), Study 1 revealed RDEs, where participants are faster for trials in which the actions span less distance. These RDEs were dependent on specific variables such as the familiarity of the routine and the amount of exposure to the stimulus materials. For example, for routines of high familiarity, participants tended to take longer when the actions were farther apart temporally within a routine. This was taken as evidence for a scanning mechanism that processes information serially. This is in contrast to the DEs that were described as reflecting an estimation mechanism, in which actions that are farther apart are more easily discriminated based on position information. This work on order information for everyday routines (Franklin, Smith, & Jonides, 2007) together with the work discussed above using an order task with numbers (Turconi et al., 2006) provide evidence for an order-related process that need not operate exclusively in numerical domains.

The Present Study

The present research was motivated by the lack of studies that have adequately assessed order processing along with recent evidence suggesting the existence of distinct order-related processes. The goal of the present study was to use a novel ordering task to provide new insights into number processing, and order processing in general. In Experiment 1 participants were shown three numbers and asked, “Are the numbers in the correct order?” This task was used to assess the ordinal processing of numbers in an attempt to overcome potential confounds of earlier studies. Very few studies have used three numbers as stimuli. The closest one is likely Brysbaert (1995; Expts 1&2) which analyzed the time to read three numbers presented on the screen from left to right. In this study, reading times increased as the distance between the first and second number increased, consistent with the RDEs discussed above for other order-related tasks. The only other studies in the literature that required participants to make judgments about more than two stimuli consist of magnitude comparison tasks (e.g, “choose the largest/ smallest”) with three and five numbers (Schulze, Schmidt-Nielson & Achille, 1991; Jou, 2003). Whereas previous work has focused on tasks with two numbers, the use of three numbers should make the relation between the ordinal positions of the items more salient and help minimize the use of a magnitude comparison strategy. Although a major goal of the present study was to investigate order processing for numbers, since numbers also inherently convey magnitude information, we adapted the same task with months of the year as stimuli in Study 2b to help rule out numerical strategies. We reasoned that if we found similar results for numbers and for months, this would suggest a general type of order processing that applies to numbers, but is not unique to them. Additionally, in order to aid in the interpretation of Experiments Study 2a & b, Study 2c required participants to indicate whether numbers were presented in forward (e.g., 12, 13, 15), backward (e.g., 15,13,12), or mixed orders (e.g., 15 12 13). This allowed for a more effective comparison of forward and backward trials for both numbers and months and could also provide evidence for the generality of these order processes with different task parameters.

Study 2a

Methods:

Participants

Twenty Universtiy of Michigan undergraduates were tested in the experiment (11 female, mean age = 20.2). One participant was removed due to accuracy being low and close to chance (56% overall; next lowest accuracy was 80%) leaving nineteen participants for subsequent analyses. Participants were all right-handed and native English speakers. Participants were paid $10.

Design

There were three variables manipulated in this experiment: direction, distance, and decade crossing. The three numbers were either ordered in the forward (e.g., 13, 14, 16), backward (e.g., 16, 14, 13), or mixed direction (e.g., 16 13 14). The largest distance between the three numbers displayed was either small (3 units) or large (6 units). Additionally, given there is some controversy regarding the representation of decade breaks on the number line (Nuerk & Willmes, 2005), we manipulated whether the three numbers cross a decade (e.g., 18 20 21) or not (e.g., 13 15 16).

Stimuli

The stimuli consisted of trials with three two-digit numbers ranging from 11-99. There were 192 unique trials total. In order for there to be an equal number of ‘yes’ and ’no’ responses, half of the trials were in the forward direction, one-fourth were backward, and one-fourth were mixed. Half of the trials included numbers that were a small distance apart, while the other half included numbers that were a large distance apart. For the small-distance trials, the distance between the first two numbers for the forward direction was always 1 unit and the distance for the second two numbers was always 2 units (e.g., 22 23 25). For the large-distance trials, the distance between the first two numbers for forward trials was always 4 units and the distance for the second two numbers was always 2 units (e.g., 22 26 28). The backward trials were created by simply reversing the direction of the forward trials (e.g., small distance: 25 23 22; large distance: 28 26 22). For the mixed trials, the first two numbers were ascending for half of the trials, and descending for the other half. This forced the participants for the forward trials (and mixed trials where the first two numbers were ascending), to pay attention to all three numbers. Additionally, there were an equal number of trials in which the three numbers crossed a decade or did not cross. To avoid the possible confound of number size (i.e., comparison of larger numbers takes longer) the mean number size for all trial-types for subsequent analysis were made comparable (mean size = 53, S.D. =1.3). Of the 192 trials, there were 24 trials for each combination of decade crossing (cross or don't cross) and distance (3 or 6 units) for the forward trials. There were 12 trials for each combination of decade crossing and distance for the remaining backward and mixed trials.

Procedure

For studies 2a-c, E-Prime experimental software (Psychology Software Tools, Inc.) was used for stimulus presentation and for recording behavioral data on Dell PC. The stimuli were presented in black with a white background in Arial 24 font.

Participants were seated 60 cm from the monitor. The sequence of events on a trial was as follows: A fixation cross appeared for 500 ms followed by the three numbers appearing side by side on the screen until a response was detected. Participants were instructed to press the '1' key on a keyboard with the left hand if the items were in the correct order (forward trials), and the '0' key with the right hand if they were in the incorrect order (backward and mixed trials). Participants were instructed to respond as quickly as possible while maintaining a high level of accuracy. Before the experimental trials began, participants went through 20 trials of practice different from those used in the experiment to assure that they understood the task. The experiment was divided into 8 blocks of 48 trials with a rest between blocks. Since there were only 192 unique trials, the second 4 blocks repeated the same stimuli in a different random order. The experiment lasted approximately 30 minutes.

Results and Discussion

Table 3.1 shows the accuracy and reaction times for each of the conditions. Since

Table 3.1. Accuracy and reaction time data for all conditions in Study 2a.

		Accuracy		Reaction Time	
		Mean	S.D.	Median	S.D.
Direction	Forward	0.93	0.04	1002.23	204.45
	Backward	0.95	0.03	961.71	196.53
	Mixed	0.77	0.10	1050.07	211.78
Decade	Cross	0.89	0.05	1016.92	205.64
	Don't Cross	0.90	0.05	983.47	199.03
Distance	Small	0.88	0.06	991.50	205.93
	Large	0.91	0.04	1009.02	200.61

there was a significant positive correlation between reaction time and error rate for all conditions (r = 0.82, p<.001) detailed analyses were performed only on reaction time data. For all analyses on reaction times, medians for each participant were calculated (to avoid outlier effects) using only the correct trials. Since the mixed trials were included in the experiment to force participants to focus on all three numbers in the forward condition they were not included in the following analyses. We expected a more uniform strategy for the forward trials indicative of order processing because participants were required to focus on all three numbers to do the task correctly, which was not true for backward trials or mixed trials in which the first two numbers were descending (e.g., 17 13 14). Consistent with this hypothesis of a fast rejection based on the first two numbers on backward trials, participants took longer for forward compared to backward trials (Forward 1002 ms, Backward, 961 ms; F(1,18) = 12.44, p = .002). Likewise, mixed trials in which the first two numbers were ascending took longer than when the first two numbers were descending (ascending = 1214 ms, descending = 971; F(1,18) = 118.972, p < . 001). Subsequent analyses focused on the interaction of distance and crossing a decade, and were specific to trials in the forward direction. For the following analyses on reaction time a two-way repeated-measures ANOVA including distance and crossing a decade was used. Figure 3.1 shows the results of the reaction time analyses. There is only an effect of distance when the trials cross a decade. This can be thought

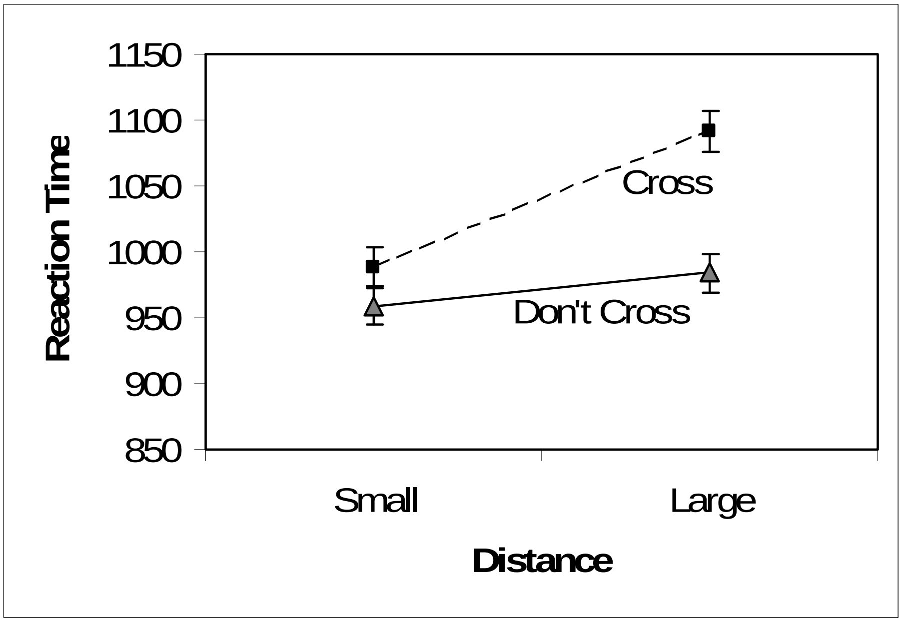


Figure 3.1- Interaction of distance and decade crossing for reaction times with numbers in the forward direction. There is no DE when the numbers are in the same decade, and a significant RDEs when the numbers cross decades. Error bars representing 95% confidence intervals are plotted for this figure and subsequent figures using methods taken from Loftus and Masson (1994).

of as a RDE in which participants take longer on trials with greater distance between numbers. There is no DE when the trials do not cross a decade. This interaction of distance by crossing a decade was significant (F(1,18) = 18.01, p = .0005). There were also significant main effects for distance (F(1, 18) = 32.18, p < .0001) and decade crossing (F(1,18) = 36.21, p < .0001). In addition, a significant positive correlation between number magnitude and reaction time (r =.158, p=.001) reveals a size effect in which participants take more time as the numbers become larger.

Whereas previous studies of number comparison have typically shown DEs, the present study reveals a different pattern of results. There were RDEs when the numbers crossed a decade and no DEs when all the numbers were within the same decade. These effects differ from what would be predicted based on the bulk of work done with order information (e.g., Brannon & Van De Walle, 2001; Brannon, 2002; Cantlon & Brannon, 2006) and are not easily accommodated into present theories of number representation. For example, the most commonly discussed type of number representation that is relevant to the present study, an analogue magnitude representation, is unable to adequately describe the present results. If participants were first comparing the first number to the second, then the second to third, they should show distance effects based on a magnitude comparison strategy. An analogue magnitude representation would predict DEs for the present task because numbers that are farther apart should be more easily discriminated compared to numbers that are closer together. Therefore this system cannot explain the RDEs in the present study.

These results provide evidence for two distinct order-related processes. The RDEs suggest that when the numbers cross a decade, participants are using a scanning process that takes longer when there is greater distance between the numbers. The lack of a DE when the numbers are within the same decade suggests another unique order-related process that will be referred to as a long-term memory checking mechanism (LTM-CM). This mechanism consists of decomposing the two-digit number and then focusing on the relevant ones digits. Since the numbers 1-9 are so well-learned, information about the order of these numbers in relation to one another may be equally accessible, allowing participants to retrieve information about the order of the numbers without being influenced by the distance between the numbers.

There are, however, additional interpretations for this interaction between decade crossing and distance. For example, participants may be accessing and scanning a single digit number line for the don’t cross trials which leads to a weak effects of distance. It is also possible that the flat distance function for numbers within a decade could be due to distance and reverse distance effects cancelling each other out. If this were the case, however, one would expect greater variance when the numbers are in the same decade, which is not the case (S.E. Cross Trials = 61.79, Don’t-Cross Trials = 54.84, n.s.).

Before commenting more on the details of these order-related processes it is important to know whether these processes are unique to numbers. For example, the scanning mechanism could be due to participants using addition or subtraction to accomplish the task. To help rule out the use of strategies specific to numbers, Experiment 2 was conducted using months of the year as stimuli. Also, given that months of year also have a natural boundary (i.e, a calendar year starts at January and ends at December), similar to the boundary at each decade for numbers, we were interested in whether effects of crossing boundaries would be similar for both types of stimuli, and thus, perhaps generalizable to other types of well-learned sequences.

Study 2b

Methods:

Participants

Twenty University of Michigan undergraduates participated in this study (13 female, mean age = 20.6). Participants were all right-handed and native English speakers. Participants were paid $10.

Design

There were three variables manipulated: direction, distance, and whether the months crossed a year-boundary. The three months were ordered in the forward or backward direction. The largest distance between the three months displayed was small (3, 4, or 5 units) or large (7, 8, or 9 units). In this study, the three months either crossed a year-boundary (i.e., the month January) or did not cross (i.e., they were between January and December).

Stimuli

The stimuli consisted of trials with three months of the year, chosen from the 12 months of the calendar year. There were 96 unique trials total. There were an equal number of forward and backward trials. Half of the trials were a small distance apart, while the other half were a large distance apart. Table 3.2 shows the inter-item distances

Table 3.2: Shows the inter item distance for each of the distances used for the forward trials in Study 2b.

	Item 1 to Item 2	Item 2 to Item 3	Example
Three	2	1	April June July
Four	2	2	October December February
Five	3	2	February May July
Seven	3	4	March June October
Eight	3	5	February May October
Nine	4	5	May September February

for each of the distances used together with example stimuli for the forward trials. The backward trials were created by reversing the direction of the forward trials. There were an equal number of cross and don't cross trials. The small distances (3, 4 or 5 units) consisted of 3, 4, and 5 trials, respectively. For the large distances (7, 8 or 9 units), there were also 3, 4, and 5 trials, respectively. This was the case for each combination of direction (forward or backward) and crossing a year (cross or don't cross).

Procedure

The timing parameters and sequence of events was the same as in Study 2a. However, the three months were presented vertically since the three months would not easily fit on the screen with horizontal presentation. Given that similar size and distance effects have been found with horizontal, vertical, and diagonal presentation the differences in presentation should not significantly affect the results (Nuerk, Weger, & Willmes, 2004). Similarly, participants were instructed to press the '1' key with the left hand if the items were in the correct order (top to bottom; forward trials), and the '0' key with the right hand if they were in the incorrect order (backward). Before the experimental trials began, participants completed 20 trials of practice different from those used in the experiment to assure that they understood the task. The experiment was divided into 8 blocks of 24 trials with a rest between blocks. With only 96 unique trials, the second 4 blocks repeated the same stimuli in a different random order. The experiment lasted approximately 30 minutes. Following the experiment, participants filled out a debriefing questionnaire in which they were asked, “Did you find yourself thinking of the months in terms of their numbers (i.e., January = 1, February= 2, etc.)”.

Results and Discussion

Table 3.3 shows the accuracy and reaction times for each of the conditions. Since there was a significant positive correlation between reaction time and error rate for all conditions (r = 0.67, p<.05) detailed analyses were performed only for reaction time data. For all analyses on reaction times, medians for each participant were calculated using only the correct trials. Given that the months in the present experiment are a repeating ordinal sequence that could cross the year boundary, participants were required to focus on all three months on a given trial in order to perform the task correctly. Therefore, subsequent analyses focused on the interaction of distance and crossing a decade, for both

Table 3.3. Accuracy and reaction time data for all conditions in Study 2b.

		Accuracy		Reaction Time	
		Mean	S.D.	Median	S.D.
Direction	Forward	0.91	0.07	2182.90	590.42
	Backward	0.90	0.07	2510.40	769.51
Decade	Cross	0.87	0.08	2395.05	681.81
	Don't Cross	0.94	0.05	2253.72	675.41
Distance	Small	0.93	0.06	2244.60	656.54
	Large	0.88	0.07	2419.80	670.40

forward and backward trials. In order to analyze reaction times, a three-way ANOVA including direction, distance and crossing a year boundary was used. Figure 3.2 shows the results of the reaction time analyses separately for the forward and backward trials.

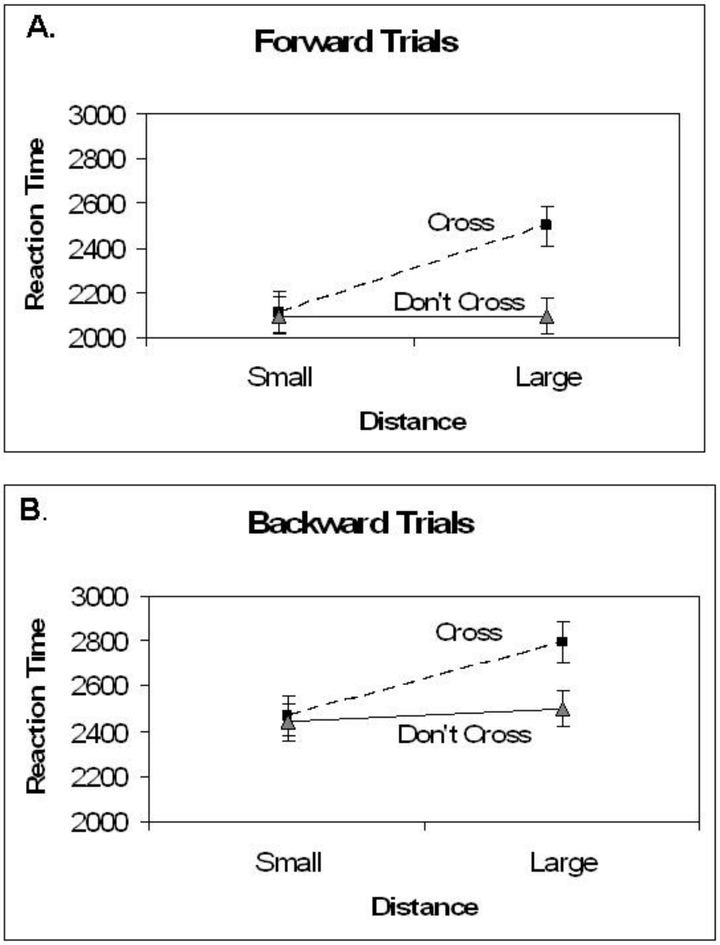


Figure 3.2- The interaction between distance and year crossing for reaction time with months of the year for a.)forward and b.)backward trials. There is no DE when the months are in the same calendar year, and a significant RDE when the months cross the January border.

For both directions, participants showed a RDE, taking longer for greater distances, only on trials in which the months cross the year boundary. There was no effect of distance when the months were within the calendar year. This interaction of distance by crossing a year was significant (F(1, 19) = 7.76, p = .01). There was also a significant main effect of distance (F(1, 19) = 31.24, p < .0001), year crossing (F(1, 19) = 4.32, p = .05), and direction (F(1, 19) = 9.925 p = .0005). The fact that there was not a significant three-way interaction (F(1, 19) = 0.95, p = .34) reveals that forward and backward trials show a similar interaction of distance with year crossing, while the main effect of direction reveals that backward trials simply take longer.

An analysis of the debriefing questions revealed that 6 out of 20 participants answered ‘yes’ to the question regarding the use of numerical strategy. Since this experiment was conducted to rule out the possibility of a numerical strategy leading to these effects, we analyzed the 14 participants claiming not to be using a numerical strategy. There still remained a significant crossing-decade by distance interaction (F(1, 13) = 14.77, p = .002). Also, although the interaction was not significant with the 6 participants who used a numerical strategy with months (F(1, 5) = 0.53, p = .49), there was a similar pattern of reaction times (see Table 3.4). This suggests that it is the order task in general, rather than specific numerical operations, that are leading to the pattern of distance effects present in both experiments.

Table 3.4. Shows the reaction times for the Crossing by Distance interaction based on strategy for Study 2b.

	Cross		Don't Cross	
	Small	Large	Small	Large
Number Strategy (n= 6)	2323.17	2576.50	2370.92	2348.16
Non-Number Strategy (n=14)	2025.03	2463.25	1981.89	1988.85

The results from Study 2b suggest that similar order-related processes are involved in processing months of the year as well as numbers. Although participants took longer and had more errors with the months as the stimuli they showed the same interaction pattern: reverse distance effects when the months cross a year boundary and no distance effects when all three months are within the same calendar year. These behavioral effects for Study 2b differ from the distance effects found with previous comparison tasks with months (Fairbanks, 1969; Friedman, 1983; Gélinas & Desrochers, 1992; Seymour, 1980a & b) and therefore are also not easily explained by an analogue magnitude representation. Therefore, these results support the findings from Study 2a that this task requires the use of specific order-related processes consisting of a scanning procedure when the stimuli cross a boundary and a LTM-CM when the stimuli do not cross. The fact that the results were not influenced by a numerical strategy (indicated by an analysis of the debriefing questionnaire) indicates that this task taps a more general type of order processing that is not specific to numbers. An analysis of the backward trials revealed a similar pattern of results. Although overall participants took longer on the backward trials, there were RDEs when the trials crossed the year boundary and no distance effect when they did not cross. This suggests that participants first check to see if the trials are in the forward order, and if not, they scan the sequence backwards to determine the order.

Since, in Experiment 1, participants made a single response for backward and mixed trials and did not need to look at all the numbers to reach a decision on the backward trials, it was not possible to compare backward trials in Studies 2a & b. Therefore in the following experiment (Study 2c) participants were required to make a separate response for forward, backward, and mixed trials. This new instruction requires participants to focus on all three numbers and allows for the comparison of the backward trials for both numbers and months. Additionally, we were able to see whether the effects for forward trials generalized to this new task.

Study 2c

Methods:

Participants

Twenty University of Michigan undergraduates were tested in the experiment (13 female, mean age = 20.3). Participants were all right-handed and native English speakers. Participants were paid $10.

Design

The design for Study 2c was the same as in Study 2a. The only differences were the instructions and the participants' responses.

Stimuli

The stimuli consisted of trials with three two-digit numbers ranging from 11-99. There were 216 unique trials total. The set of stimuli were designed as in Study 2a except for the addition of trials to create an equal number of forward, backward, and mixed trials. Of the 216 trials, there were 18 trials for each combination of decade crossing (cross or don't cross) and distance (3 or 6 units) for all directions.

Procedure

The sequence of events on a trial was as follows: A fixation cross appeared for 500 ms followed by the three numbers appearing side by side on the screen until a response was detected. Participants were instructed to respond with their right hand pressing the ‘1’ key on a keyboard if the items were in the forward order, the ‘2’ key if they were backward, and the ‘3’ key if they were mixed. Participants were instructed to respond as quickly as possible while maintaining a high level of accuracy. Before the experimental trials began, participants went through 20 trials of practice different from those used in the experiment to assure that they understood the task. The experiment was divided into 8 blocks of 54 trials with a rest between blocks. Since there were only 216 unique trials, the second 4 blocks repeated the same stimuli in a different random order. The experiment lasted approximately 35 minutes.

Results and Discussion

Table 3.5 shows the accuracy and reaction times for each of the conditions. Since there was a significant positive correlation between reaction time and error rate for all conditions (r = 0.91, p<.001) detailed analyses were performed only on reaction times.

Table 3.5. Accuracy and reaction time data for all conditions in Study 2c.

		Accuracy		Reaction Time	
		Mean	S.D.	Median	S.D.
Direction	Forward	0.89	0.15	1247.50	297.53
	Backward	0.83	0.19	1379.75	287.11
	Mixed	0.75	0.24	1421.08	280.13
Decade	Cross	0.81	0.18	1389.53	292.74
	Don't Cross	0.85	0.22	1319.06	306.60
Distance	Small	0.82	0.21	1347.08	314.91
	Large	0.83	0.19	1365.11	288.26

For all analyses, medians for each participant were calculated using only the correct trials. The main analysis of interest was the interaction of distance and crossing a decade for all three directions. Forward and backward trials were analyzed separately from mixed in order to make comparison easier with Study 2b. Also, mixed trials are different from forward and backward trials in that they are not an ordered sequence. In order to analyze reaction times, a three-way ANOVA including direction (forward/backward), distance and crossing a year boundary was used. Figure 3.3 shows the results of the reaction time analyses separately for the forward and backward trials. For both directions, participants showed a RDE, taking longer for greater distances only on trials in which the numbers cross a decade. There was no effect of distance when the numbers were within a decade. This interaction of distance by crossing a decade was significant (F(1, 19) = 16.79, p = .001). There was also a significant main effect of distance (F(1, 19) = 26.86, p < .0001), decade crossing (F(1, 19) = 17.44, p = .05), and direction (F(1, 19) = 21.48, p < .0001). The insignificant three way interaction (F(1, 19) = 0.69, p = .41) reveals that forward and backward trials show a similar interaction of distance with decade crossing, while the main effect of direction reveals that backward trials are simply taking longer. The results differed for the mixed trials, with no significant interaction of distance and decade crossing, and no significant main effects for distance. There was however a trend towards a main effect for decade crossing (F(1, 19) = 3.49, p = .08), with participants taking longer when the trials cross a decade. In addition, there was a significant positive correlation between number magnitude and reaction time (r =.18, p=.001) which is evidence for a size effect in which participants take more time as the numbers become larger.

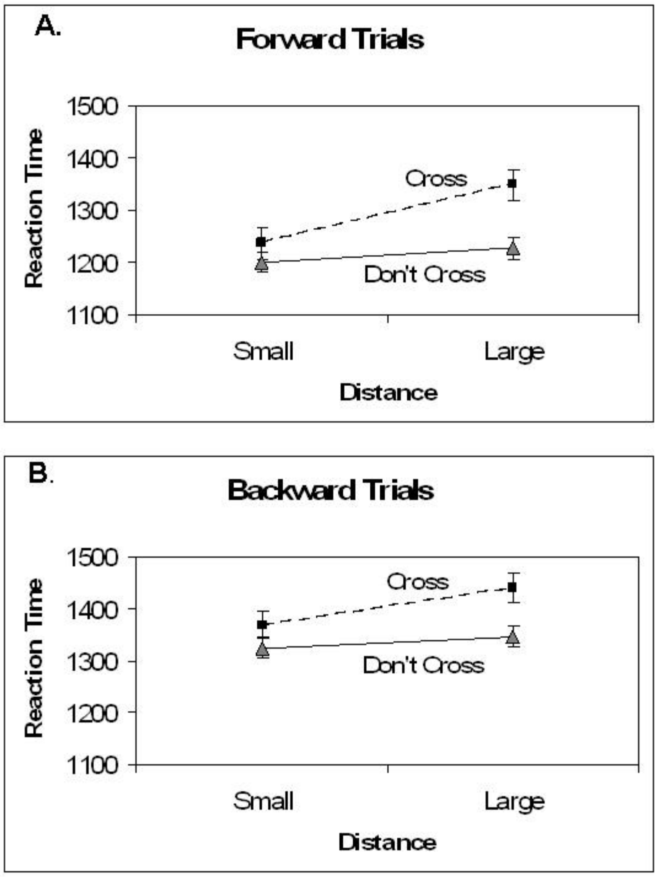


Figure 3.3- The interaction of distance and decade crossing for reaction times with numbers in the a.)forward and b.)backward direction. There is no distance effect when the numbers are in the same decade, and a significant reverse-distance effect when the numbers cross decades.

The results from Study 2c replicate and extend the findings of Study 2a & b. For both forward and backward trials participants show RDEs for cross trials, and no distance effect for trials that do not cross. This interaction was present in Study 2a for forward trials, and Study 2b for forward and backward trials. These results strengthen the claim that there are distinct order-related processes, namely a scanning mechanism and LTM-CM that operate with both ordered numerical and non-numerical stimuli under different task parameters.

General Discussion

Given the evidence provided in Studies 2a-c for specific order-related processes it is important to consider how these findings relate to current knowledge of number representation as well as the representation of order information in general. With regard to number representation, these results cannot be explained by a typical analogue magnitude representation. However, a proposal has been made that there is an additional representation, termed the count-list, which represents positive integers and allows for counting because it contains a generative system capable of creating an infinite list (Carey, 2004). This could be considered relevant to the present findings considering the use of two-digit numbers and the similarity between the ideas of counting and scanning a number line. However, it is important to note that the months of the year would not be considered a type of count-list given that there are a fixed number of months. Additionally, the lack of mathematical operations needed when scanning through the months makes the count-list inadequate at describing the present results. So although the RDEs in Studies 2a and 2c could be consistent with counting (or possibly other mathematical operations), the results of the months and number study together suggest that rather than counting numbers, participants are scanning through a list. This list of numbers has typically been thought of as a mental number line with certain properties based on analogue magnitude theories of number representation. Given the unique order-related processes suggested by the current task, it is important to consider how these processes fit with the traditional model of number representation.

One important issue the present experiment can address is how the break between decades is represented on the number line. The interaction between distance and decade crossing suggests that there is a break in the number line at each decade, consistent with work by Nuerk and colleagues (Nuerk, Weger, Willmes, 2001). The present results suggest that when numbers are within the same decade they are decomposed, and only the "ones" units are compared. Since the numbers 1-9 are well-learned, participants can simply retrieve this information without being influenced by the distance between the numbers. When the numbers cross a decade, participants use a scanning strategy to reach a decision that takes longer when the numbers span a greater distance. The finding that the numbers are decomposed is consistent with work showing that both the "ones" and "decade" units are relevant in number comparison tasks. The evidence for these claims comes from compatibility effects in which reaction time is faster when comparing the size of two two-digit numbers if both the ones and tens units are larger or smaller than the comparison number regardless of overall distance (e.g., 12 & 45 are compatible and 25 & 31 are incompatible; Nuerk, Weger, Willmes, 2004; Nuerk & Wilmes, 2005). Dehaene and colleagues (1990), however, showed that for a task that involves assessing whether a given number is larger or smaller than some target number, there were no discontinuities in the number line at decade breaks which supports a holistic view of number representation.

These seemingly contradictory findings for decomposed vs. holistic processing of two-digit numbers can perhaps be reconciled in the context of the present findings. Our findings suggest that there are multiple processes operating in parallel, a scanning mechanism that leads to a decision for cross-decade trials and treats the numbers holistically, consistent with Dehanane and colleagues (1990), as well as a LTM-CM which makes use of decade and tens unit information separately, consistent with Nuerk and colleagues (Nuerk, Weger, Willmes, 2001; Nuerk & Wilmes, 2005). Additionally, the boundary effects in Study 2b with months suggest the possibility that decade effects are not only due to the decomposition of the numbers, but also may be related to the way in which numbers are learned and stored in memory. After all, months are in no way decomposed, but there are still significant boundary effects which are likely due to the way people learn and think about the months as an ordered set of items.

One notable difficulty that traditional analogue magnitude models of number representation have in explaining the present results has to do with the size effect. The size effect is typically taken as evidence for either a compressed number line as numbers get larger (Dehaene, 2003) or for increased variability in ordinal position as numbers get larger (Gallistel & Gelman, 1992, 2000). These models suggest that scanning should be faster for larger numbers because they are closer together, which is contrary to our findings. The size effect as interpreted in the context of the present study suggests longer scanning time for larger numbers. These contrary findings are consistent with current work dissociating size and distance effects (e.g., Verguts, Fias, & Stevens, 2005; Verguts & Van Opstal, 2005) that suggest size effects are not inherently tied to a mental number line and instead may be task-related. Results from these studies show that tasks such as number naming, parity judgment, and same/different judgments show DEs but no size effects. This suggests that participants are accessing a mental number line that does not obey Weber's law (i.e., it does not become compressive as number size increases with large numbers receiving a coarser mental representation than smaller ones; for a review see Krueger, 1989). Likewise, the lack of a size effect for months also supports the idea that size effects need not be incorporated into representations of sequential information in general.

There have been other studies that have found similar results to the present study. Turconi and colleagues (2006) compared performance on a magnitude comparison task where participants chose the larger of two single-digit numbers to an order task in which participants were asked whether the two numbers were in the correct order. The order instruction led to a RDE for adjacent ascending numbers and DEs for all other number sequences. The RDEs in their order task was interpreted as an order-specific process; however, there remains the possibility that these effects are due to the special status of adjacent numbers in memory. Therefore the results from Turconi and colleagues (2006) do not conclusively show that the RDE is due to participants scanning a mental number line. The fact that we found RDEs using non-adjacent triplets suggests that the reverse distance effect found in these order tasks is in fact related to a scanning mechanism.

In another study, Brysbaert (Experiment 4; 1995) used a task in which participants named a target number shown at various stimulus onset asynchronies (SOAs) after a prime. A plot of the interaction of distance and decade crossing revealed a similar pattern to our results for each of the SOAs and was statistically significant for the SOA of 400 ms. There was no slope for numbers within a decade and a positive slope for numbers that cross a decade. The RDE in this experiment was considered a type of automatic priming in which activation of the prime in memory facilitates the processing of numbers close to the prime. While priming could potentially explain the RDEs in the present experiment, the large magnitude of the reverse distance effects reported here (>100ms) compared to those found in the Brysbaert study (20 ms) suggests that scanning may be a more apt mechanism.

Conclusion

The present work adds to our knowledge of number processing by showing that numbers, as ordinal sequences, can be processed by distinct order-related mechanisms. We provide evidence for a scanning mechanism for numbers within a decade and a LTM-CM for numbers that cross a decade boundary. The study with months helped to demonstrate that the order processes revealed by the present task are not dependent on numerical processing. By using a novel task that emphasizes the processing of order information, the present results have revealed a more complete view of number processing and, more generally, the processing of other well-learned ordered sequences.

CHAPTER 4

The Role of the IPS in Representing Magnitude and Order Information for Numbers: Dissociating Numerical Distance from Participants' Strategies.

Abstract

The role of the intraparietal sulcus (IPS) in the representation of numerical magnitude is well-established. Recently, there has also been speculation that the IPS is involved in the representation of ordinal information as well. These claims, however, tend to overlook the fact that all neuroimaging paradigms that have assessed either magnitude and/or order processing show behavioral distance effects (a numerical comparison is easier when the stimuli span a greater distance). Therefore, it may be that activation of the IPS is due to production of distance effects, or it may be that it is commonly involved in representation of magnitude and order information. The current study used fMRI to compare a magnitude task in which participants show distance effects to an order-judgment task that yields reverse distance effects. The results reveal activation of the IPS for both the magnitude and order tasks that is based on participants' strategies as opposed to the actual distance between the numbers. This leads to the conclusion that the IPS represents a mental number line, and that accessing this line can lead to distance effects when participants compare magnitudes and to reverse distance effects when participants check for order.

Introduction

While numbers are most frequently used to indicate magnitude (e.g., there are *three* apples on the table), there are other ways in which numbers can be used. For example, numbers can be used to specify ordinal, or position information (e.g., the runner came in *3rd* place). While these two features of numbers are seemingly different, a recent paper about the neural basis of number processing by Jacob & Nieder (2008) makes the claim that magnitude and order information are processed by similar brain regions. However, this claim rests on a thin evidential base in that it relies almost exclusively on tasks that assess numbers in terms of magnitude. These tasks often involve asking participants to pick out the smaller or larger of two numbers, or to decide whether a given number is smaller or larger than some target number. These magnitude-comparison tasks lead to a prominent behavioral effect, known as the distance effect (DE), which refers to the fact that comparison of two numbers is accomplished more quickly and with greater accuracy when they span a greater distance (Dehaene et al., 1990; Moyer & Landauer, 1967). This fact has led to the view that numbers are represented on an analog mental number line for which it is more difficult to discriminate numbers that are closer together (Dehaene, 2003; Dehaene & Changeux, 1993; Gallistel & Gelman, 2000; Wynn, 1998; Whalen et al., 1999).

There have also been neuroimaging studies investigating the neural mechanisms of these magnitude-comparison tasks. This work shows that the intraparietal sulcus (IPS) becomes active in a distance dependant manner, with greater activation for numbers that are closer together in magnitude (Fulbright et al., 2003; Kaufmann et al., 2005; Piazza et al., 2004, 2007; Pinel et al., 1999, 2001, 2004; Wood, Nuerk, & Wilmes, 2006). Other evidence for the role of the IPS in magnitude processing comes from patients with lesions that include this region who show deficits specific to magnitude-comparison tasks (Lemer, et al., 2003; Dehaene & Cohen, 1997). Also, it has been shown that the use of repetitive transcranial magnetic stimulation to the IPS results in deficits on magnitude-comparison tasks (Sandrini, 2004). Taken together, this body of research has led to the view that the IPS is involved in the representation of a mental number line that is accessed when magnitudes are compared (Ansari et al., 2006a; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Piazza et al., 2004; Pinel et al. 2001, 2004).

The few studies that have investigated the processing of ordinal information about numbers suggest that the processing of magnitude and order information may differ. Turconi and colleagues (2006) assessed order processing by having participants decide whether two numbers were in the correct order. Performance on this task was compared to a magnitude-comparison task of choosing the larger (or smaller) of the two numbers. When participants were shown two numbers and asked the question, “Are the numbers in the correct order?”, they showed reverse distance effects (RDEs) if the small-distance numbers were adjacent and ascending (e.g., 6_7 is faster than 4_7) and DEs for all descending pair comparisons; however, when they had to choose the larger or smaller of two numbers, they showed DEs regardless of adjacency or whether the numbers were ascending or descending. The RDE suggests a scanning mechanism that accesses each number serially, taking longer when they span a greater distance, and it may be a distinct order-related process. Supporting evidence comes from Study 2, (Franklin et al., 2006), which shows that when participants are deciding whether three two-digit numbers are in the correct order, RDEs are also seen for both ascending and descending number triplets that are non-adjacent.

There appears to be a discrepancy here. On the one hand, behavioral evidence indicates a dissociation between the processes involved in operations having to do with magnitude versus order. On the other hand, Jacob and Nieder (2008) cite evidence for the similarity of these processes based largely on a recent fMRI study by Fias et al. (2007). In this study, brain activation during an order task with letters (i.e., which of two letters is later in the alphabet) was compared with that of a magnitude task with numbers (i.e., which of two numbers is larger). The IPS was shown to be active in both tasks. The authors, therefore suggest that the IPS is responsible for processing both magnitude and order information. However, there is an alternate interpretation of these data: that the IPS is active for both magnitude and order tasks, not because this region reflects magnitude and order processing per se, but because it reflects the DEs that are present for both tasks. That is, in both tasks it was easier to make a decision when either the numbers or letters were farther apart[1]. This is so for all neuroimaging research that has used magnitude and/or order tasks; they all resulted in distance effects. So, is the IPS commonly responsible for the processing of order and magnitude, or is the IPS commonly responsible for production of distance effects? That is the question we address.

The Present Study

In order to address this issue, we used fMRI to compare a magnitude task (i.e., "Is the number larger/smaller than 65?") that shows DEs with an order task (i.e., "Are the

---

[1] Although Fias et al. (2007) do not provide behavioral data regarding distance effects, these tasks have previously been reported to show distance effects (see Dehaene et al., 1990 and Jou, 1997).

numbers in the correct order?") that shows RDEs in the same group of participants. Several aspects of this study are an advance. First, we use a common set of stimuli (numbers) for both tasks. Second, by using a task that shows RDEs, we investigate the role of the IPS in number representation by dissociating the effects of numerical distance and participant strategy. If the IPS is sensitive to the distance between numbers, it should be more active when the numbers are closer together for both the magnitude and order task. If the IPS is sensitive to participants' strategies, then the activation should be consistent with DEs for the magnitude task and RDEs for the order task (i.e., more active for the more difficult trial type in both tasks). It is also possible that the IPS is only sensitive to tasks that show DEs behaviorally and therefore will only be active for the magnitude task. Finally, in addition to better understanding the role of the IPS in the representation and processing of magnitude and order information, this study also allows us to identify other brain regions that are both common and unique to these two tasks.

Study 3

Methods:

Participants

Seventeen University of Michigan students (University of Michigan undergraduate and graduate students; age range 18-28; mean age = 21.8; 7 male) participated in this study. All participants were right-handed and native English speakers with normal or corrected-to-normal vision. Participants were health-screened and informed consent was obtained in accordance with the University of Michigan Institutional Review Board. Participants were paid an average of $40, which included a bonus based on performance. Two participants were removed from imaging analyses due to movement exceeding 7 mm (see Table C1 in the appendix for the means and standard deviations of the motion parameters for the remaining 15 subjects).

Behavioral tasks

E-Prime experimental software (Psychology Software Tools, Inc.) was used for stimulus presentation and for recording behavioral data. The stimuli were presented in black with a white background and were projected onto a screen at the head of the scanner. The participants viewed the screen via a pair of goggles with a mirror attached. Responses were collected using two 5-button response units that attached to the left and right hands (MRI Devices Corp. Pittsburgh, PA). Participants received 8 runs of the order task, followed by 2 runs of the magnitude task. Since pilot testing revealed that the magnitude task weakened the RDEs for the order task, the magnitude task was always tested after the order task. Given that the results of the magnitude task are in close accordance with those of Pinel et al., (2001) whose task parameters were nearly identical, this ordering likely had little influence on the performance in the magnitude task. Each run consisted of 20 trials, for a total of 160 order trials and 40 magnitude trials. Participants were given instructions for the relevant task before each run. Before scanning, the participants went through 20 trials of practice for each task to familiarize them with the tasks. The entire protocol lasted approximately 1.5 hours.

Order Task

Stimuli

The set of stimuli for the order task consisted of trials with three two-digit numbers ranging from 11-99. The three numbers were ordered in the forward (e.g., 13, 14, 16), backward (e.g., 16, 14, 13), or mixed direction (e.g., 16 13 14). The largest distance among the three numbers displayed was either small (3 units) or large (6 units). Additionally, in that there is some controversy regarding the representation of decade breaks on the number line (Nuerk, Weger, & Willmes, 2001), we manipulated whether the three numbers crossed a decade (e.g., 18 20 21) or not (e.g., 13 15 16). In order for there to be an equal number of ‘yes’ and ’no’ responses, half of the trials were in the forward direction, one-fourth were backward, and one-fourth were mixed. Half of the trials included numbers that were a small distance apart, while the other half included numbers that were a large distance apart. For the small-distance trials, the distance between the first two numbers for the forward direction was always 1 unit and the distance for the second two numbers was always 2 units (e.g., 22 23 25). For the large-distance trials, the distance between the first two numbers for forward trials was always 4 units and the distance for the second two numbers was always 2 units (e.g., 22 26 28). The backward trials were created by simply reversing the direction of the forward trials (e.g., small distance: 25 23 22; large distance: 28 26 22). For the mixed trials, the first two numbers were ascending for half of the trials, and descending for the other half. This forced the participants to pay attention to all three numbers for the forward trials and for the mixed trials on which the first two numbers were ascending. There were an equal number of trials in which the three numbers crossed a decade versus not crossing. To avoid the possible confound of number size (i.e., comparison of larger numbers takes longer) the set of stimuli was created such that the mean number magnitude for all trial-types was made equivalent (mean size = 53, S.D. =1.3). Subsequent analyses focus on the forward trials which are most indicative of order processing because participants were required to focus on all three numbers to do the task correctly. This was not true for backward trials or mixed trials in which the first two numbers were descending (e.g., 17 13 14) where participants could respond correctly by looking only at the first two numbers.

Procedure

The sequence of events on an order trial was as follows: A yellow square appeared for 200 ms to alert participants followed by a blank screen for 1800 ms. Next, the three numbers appeared side by side on the screen for 2000 ms. Finally, a fixation cross appeared for between 6000-14000 ms randomly jittered in 2-second increments. Each trial lasted 14 seconds on average. Participants were instructed to respond with the left hand index finger if the items were in the correct order (forward trials), and right hand index finger if the numbers were in the incorrect order (backward and mixed trials). Participants were instructed to respond as quickly as possible while maintaining a high level of accuracy.

Magnitude Task

Stimuli

The magnitude task was similar to that of Pinel et al., (2004). The only differences were that we included only "near" and "far" trials, and we jittered the fixation time. The stimuli consisted of two-digit numbers ranging from 35-96. Half of the trials included numbers that were a small distance from 65 (near; 61-64_66-69), while the other half included numbers that were a large distance from 65 (far; 33-44_87-96).

Procedure

The sequence of events on a magnitude trial was as follows: A yellow square appeared for 200 ms to alert participants followed by a blank screen for 1800 ms. Next, a single number appeared on the screen for 200 ms. Finally, a fixation cross appeared for between 7800-15800 ms randomly jittered in 2-second increments. Each trial lasted 14 seconds on average. Participants were instructed to respond with the left hand index finger if the number was less than 65 and the right hand index finger if the number was greater than 65. Participants were instructed to respond as quickly as possible while maintaining a high level of accuracy.

Image acquisition and pre-processing

Images were acquired on a GE Signa 3T scanner equipped with a standard quadrature headcoil. Head movement was minimized using foam padding and a cloth restraint strapped across participants' foreheads. Experimental tasks were presented using

E-Prime software (Psychology Software Tools, Inc.). Functional $T2*$ weighted images were acquired using a spiral sequence with 40 contiguous slices with 3.44×3.44×3 mm voxels (repetition time (TR)=2000 ms, echo time (TE)=30, flip angle=90, and field of view (FOV)=22). A T1 weighted gradient echo (GRE) anatomical overlay was acquired using the same field of view and slices as the functional scans (TR=250, TE=5.7, and flip angle=90). Additionally, a 106-slice high resolution T1 weighted anatomical image was collected using spoiled gradient-recalled acquisition in steady state (SPGR) imaging (TR=10.5, TE=3.4, flip angle=25, FOV=24, 1.5 mm slice thickness). Each SPGR was corrected for signal inhomogeneity (G. Glover and K. Kristoff, http://www-psych.standford.edu/~kalina/SPM99/ Tools/vol_homocor.html) and skull-stripped using FSL's Brain Extraction Tool (http://www.fmrib.ox.ac.uk/fsl). These images were then normalized to the MNI template (avg152t1.img) using SPM2 (Wellcome Department of Cognitive Neurology, London). Functional images were corrected for slice-time differences using 4-point sinc interpolation (Oppenheim et al., 1999) and head movement, using MCFLIRT (Jenkinson et al., 2002). Spatial normalization transformations and 8mm FWHM isotropic Gaussian smoothing were applied to all functional images prior to analysis using SPM2. All analyses included a temporal high-pass filter (128 s) and each image was scaled to have a global mean intensity of 100.

Image Analysis

Whole-brain analyses were conducted using the General Linear Model implemented in SPM2. For both the magnitude and order tasks, event onset times for the trials were convolved with the canonical hemodynamic response function (HRF).

Contrast images for each participant were subjected to a random-effects group analysis (see Figures C.2 & C.3 for the order and magnitude task design matrices). In order to address the question of how the distance between numbers affects activations for the magnitude task versus the order task, we identified voxels that are activated in both tasks (common regions) and those that are specific to one of the two tasks (unique regions). This made sense as a first step analysis in that it reveals the global patterns of activation independent of the various hypotheses concerning a specific region's activation. In order to determine the common regions both tasks had to show activation that was significant at $p <.01$ uncorrected for multiple comparisons, with more than 20 contiguous voxels. The unique regions were determined to be areas that showed activation at $p<.001$ in only one of the tasks, showed no activation in the other task at an even lower threshold of $p < 0.05$ uncorrected, and consisted of more than 20 contiguous voxels (see Fan et. al., 2003 and Wager et al., 2005 for similar thresholding techniques).

With four possible contrasts of interest (magnitude near>far, magnitude far>near, order near>far, order far>near), we investigated which between-task contrasts would reveal common regions. If the activation is dependent on the distance between numbers then the two sets of contrasts showing similar activation should be (1) magnitude near>far/order near>far and (2) magnitude far>near/order far>near. If, on the other hand, activation is related to the participants' strategies, reflected by the behavioral effects, then the similar contrasts should be (1) magnitude near>far/order far>near (i.e., hard>easy) and (2) magnitude far>near/order near>far (i.e., easy>hard). Based on these results we also investigated which activations were unique to each of the tasks. (See Appendix A for information regarding why the analyses for this study were done by collapsing across the decade crossing for variable.)

Results

Behavioral Results

For all analyses of reaction times, medians for each participant were calculated (to avoid outlier effects) using only the correct trials. The data were analyzed using a 2 x 2 repeated-measures ANOVA with distance (near vs. far) and task (magnitude vs. order). The results are shown in Figure 4.1 which shows that for the magnitude task, participants show DEs, taking longer and having more errors for near versus far trials, whereas in the order task participants show RDEs, taking longer and having more errors for the far trials. This distance by task interaction was significant for both reaction times (F(1, 14) = 22.18, p < .0001) and accuracy (F(1, 14) = 7.27, p = .01). There was also a main effect of task for reaction time (F(1, 14) = 288.00, p < .0001) with participants taking longer for the order task (1046.9; S.E. = 30.8) compared to the magnitude task (656.1; S.E. = 21.1). The greater difficulty of the order task should not influence the interpretation of the fMRI activations between tasks since the main effect of task is present for both near and far trials, and would subsequently be cancelled out when calculating the individual task activations. These behavioral results are consistent with the hypothesis that different strategies are engaged for the magnitude and order tasks.

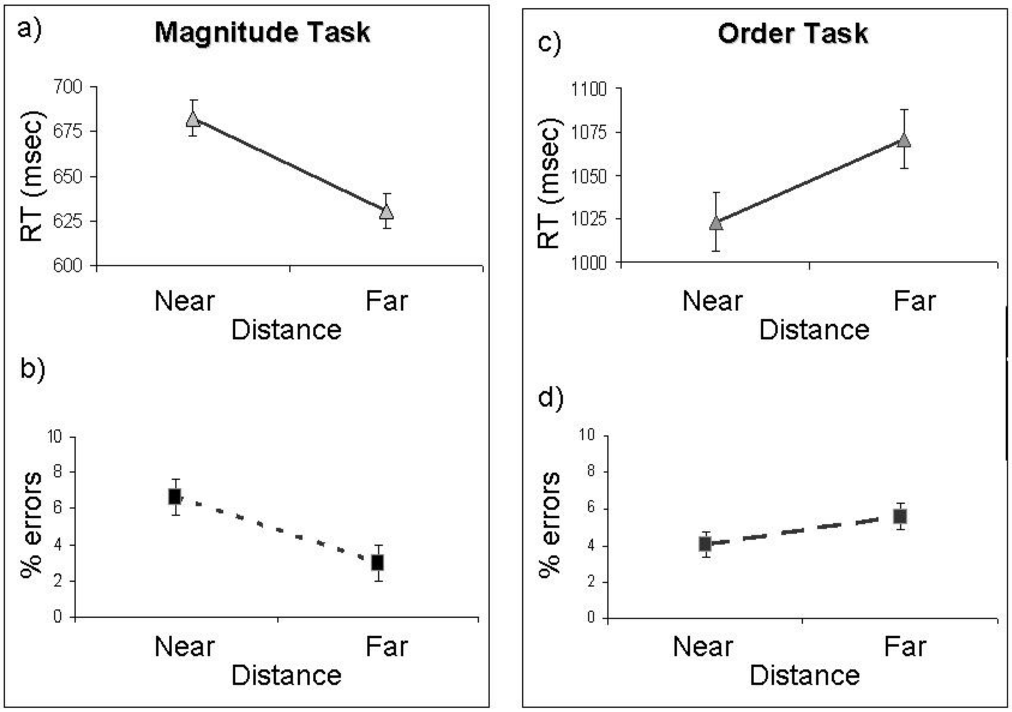


Figure 4.1. Reaction times and accuracies for the magnitude task (a,b) and order task (c,d). Participants show a DE for the magnitude task, and a RDE for the order task.

fMRI Results

Common task activations: Only 2 of the 4 possible comparisons between the magnitude and order task revealed common activations. These comparisons and the resulting common brain activations are displayed in Figure 4.2a,b. The regions that were common to both tasks responded to participants' strategy with some regions showing greater activation for the more difficult comparison in each task, while other regions showed greater activation for the easier comparison. There were no common regions that were modulated by the actual distance between the numbers. Specifically, the IPS was active for the hard>easy comparison in both tasks (i.e., magnitude near>far and order far>near). The MNI coordinates of this activation (-40, -52, 52) are within a few millimeters of those reported in previous number processing studies (Dehaene et al., 1999; Naccache & Dehaene, 2001; Piazza et al., 2004; Pinel et al., 1999, 2001; Presenti et al., 2000). The regions common to the easy>hard comparison (i.e., magnitude far>near and order near>far) include the left STG, right insula, and the left/right caudate/putamen (see Table 1 for details on the activations in each task).

Unique activations: In addition to the activations shared by the magnitude and order task, we also investigated the activations unique to each of the tasks. These results are displayed in Figure 4.2 c-f with the specific activations listed in Table 4.1. For the hard>easy contrast, activations unique to the magnitude task (magnitude near>far) consisted of the left IPS and left superior parietal lobule (SPL). The one unique activation to the order task (i.e., order near>far) was found in the cerebellar vermis. For the easy>hard contrast, activations unique to the magnitude task (magnitude far>near) included the right STG, left MTG, right fusiform gyrus, insula, caudate, and the posterior cingulate. Activations unique to the order task for this contrast (order far>near) were in the right STG, right IFG, and right MTG. (See Appendix B for results from the whole brain analysis).

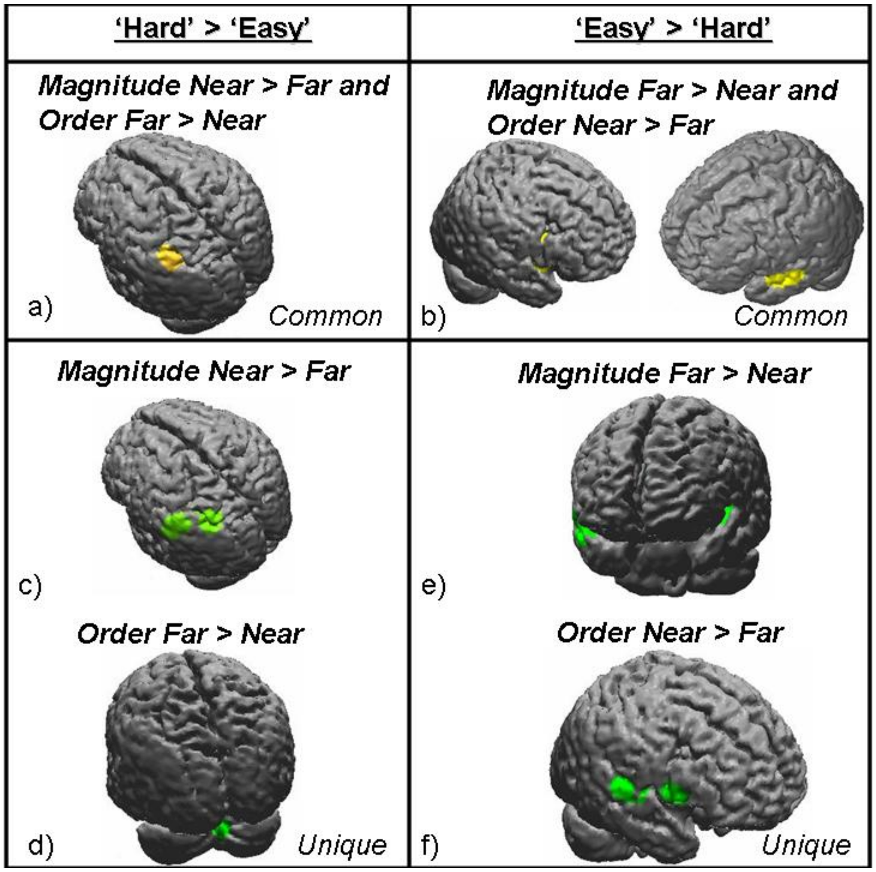


Figure 4.2. Common and unique activations for the magnitude and order task. There were common activations for both the (a) magnitude and order task hard>easy contrast and the (b) magnitude and order easy>hard contrast. The unique activations for magnitude and order are displayed in panels c-f. (see Figure C.1 in for a slice view)

Table 4.1. Common and unique regions active for both order and magnitude tasks.

Regions	BA	x	y	z	# voxels	Activity (Peak t-score)			
						Mag Near>Far	Mag Far>Near	Order Near>Far	Order Far>Near
Common Regions									
Hard>Easy									
Left IPS	40	-40	-52	52	27	3.45			3.11
Easy>Hard									
Left STG	22/21	-56	-8	-4	52		3.71	3.01	
Right Insula	13	36	0	-2	54		3.82	3.51	
Right Caudate		20	-34	20	461		3.03	3.26	
Right Rolandic Operculum	13	42	-2	16	194		3.41	4.08	
Left Caudate		-22	-34	20	155		2.78	3.45	
Right Caudate Nucleus		20	2	20	58		3.33	2.96	
Unique Regions									
Mag Near>Far									
Left IPS	40	-42	-44	46	53	4.06			
Left IPS	40	-58	-42	48	44	4.88			
Left SPL	7	-34	-64	52	26	4.51			
Mag Far>Near									
Left Parahippocampal Gyrus	36/35	-26	-30	-24	39		4.33		
Right STG	21/22	56	2	-12	94		4.88		
Right Fusiform Gyrus	37	38	-56	-14	37		4.78		
Right Fusiform	37	40	-36	-6	113		4.82		
Left MTG	21/22	-44	-28	-8	32		6.09		
Left Insula Lobe	13	-38	-10	-4	35		4.21		
Left MTG	39	-42	-52	10	61		4.75		
Caudate		-18	-36	14	27		4.42		
Caudate		-6	12	18	182		4.67		
Right Insula	13	32	18	18	23		5.27		
Posterior Cingulate	31	20	-48	24	31		5.77		
Order Far>Near									
Cerebellar Vermis		2	-74	-26	35				4.45
Order Near>Far									
Right STG	22	58	-18	4	44			4.45	
Right IFG	47	42	12	10	174			3.94	
Right MTG	21	46	-40	10	43			4.89	

Discussion

The present results help clarify the role of the IPS in the representation of magnitude and order information for numbers. Previous studies have shown that the IPS responds in a distance-dependent manner in magnitude comparison tasks with more recent work implicating this same area in an order task with letters. This is the first study to show that activity in the IPS is not tied to the behavioral DEs present for these types of tasks. This was accomplished by dissociating the effects of numerical distance from participants' strategies by eliciting DEs for a magnitude comparison task and RDEs for an order task. While the DEs are consistent with a magnitude comparison process that can more easily discriminate numbers that are farther apart, the RDEs suggest a scanning mechanism that accesses the numbers serially leading to faster response times when the numbers are closer together.

These results show that activity in the IPS reflects these behavioral indices of participants' strategies rather than being related to the actual distance between numbers. For the magnitude task, we replicated the findings from a number of studies showing greater IPS activation when comparing near to far trials (Ansari et al., 2006a; Fulbright et al., 2003; Kaufmann et al., 2005; Piazza et al., 2004, 2007; Pinel et al., 1999, 2001, 2004). The order task comparison that produced the most similar activation was consistent with the RDEs, with greater activation for far trials. Therefore, for both the magnitude and order task, the IPS showed greater activation on the difficult trials compared to the easy trials (i.e., hard>easy). These findings strengthen the claims of the involvement of the IPS in representing a mental number line which can represent both magnitude and order information. The novel finding is that different processes are involved in accessing this mental number line; a magnitude comparison process reflected by the DEs and a scanning process reflected by RDEs.

While the current claim is that IPS activation is tied to order and magnitude processing, an alternative interpretation is that this activation is instead related to difficulty within a task, and is therefore more responsive in both tasks for the more difficult comparison (i.e., near trials for magnitude and far trials for order). However, there have been recent studies which show distance effects in the IPS even for paradigms in which the participants are not required to make a response. For example, both Ansari et al. (2006b) and Piazza et al. (2004) have shown IPS activation relates to numerical distance with passive viewing of changes in numerosity of stimulus arrays. Therefore, this suggests that IPS activation can not fully be accounted for by within task difficulty.

In addition to the IPS's involvement for the hard>easy contrast for both the magnitude and order tasks, our analyses revealed unique areas as well. The unique activations for the magnitude task were in the IPS and SPL, which were very close to the common regions. The most conservative interpretation is that the magnitude near>far contrast simply activated a more extensive region of the IPS than the order task. This makes sense given that the distance between near and far trials was much greater for the magnitude task (average near distance = 2.5, average far distance = 26.5) then for the order task (near = 3, far = 6). It is, however, also possible that there is a functional distinction between the IPS and SPL. For example Dehaene's (1992) triple-code model proposes that in addition to the IPS, which represents magnitude in terms of a mental number line, other parietal regions are engaged in other aspects of number comparison tasks. For example, the posterior superior parietal system is thought to play a role in orienting verbal and visual attention when accessing numerical magnitude information (Dehaene et al., 2003). Therefore, the SPL in particular could be involved in the comparison process which leads to DEs.

The unique activation for the order far>near contrast was seen in the cerebellar vermis. This is consistent with other studies suggesting the involvement of the vermis in processing order information. For example, the cerebellum is involved in sequential operations for both word and sentence production (Fabbro et al. 2000) and lesions to the cerebellar vermis are associated with reading errors largely due to the transposition of letters (Moretti et al., 2002). Therefore, this area of the cerebellum may be involved in the scanning process that results in RDEs.

Besides the common activations when comparing hard>easy for the magnitude and order tasks, there were also common regions for the two tasks for the easy>hard comparison. These regions have been demonstrated to be involved in various aspects of memory retrieval. For example, in memory tasks in which participants first study words and pictures and are later given a recognition test, there is greater activation during recognition for old compared to new stimuli in the left STG (Woodruff et al., 2005). While these activations were posterior to those found in the present study, more anterior activations have also been reported when participants use insight to solve problems (Jung-Beeman et al., 2004) which presumably also requires the retrieval of semantic information. Also there are a number of studies that localize the N400, which reflects a semantic context effect, to a similar region of the left STG as well as the caudate nucleus and insula which were also activated in the present study (Friederici et al., 2003; Kotz et al., 2002; Rissman et al., 2003; Van Petten & Luka, 2006).

This pattern of activation suggests an additional mechanism that can be used in these number comparison tasks: a long-term memory retrieval process. In the magnitude task, participants likely encode the far numbers as being big or small, and are able to retrieve this information to do the comparison in addition to relying on a mental number line. Likewise, for the order task, participants likely make use of memorized facts about the order of numbers in order to decide whether the numbers are in the correct order.

There were also unique activations for the easy>hard comparison for each of the tasks. Many of these activations were similar to those from the common analysis such as the STG, MTG, insula, and caudate, and could indicate that the retrieval of different types of information for the two tasks results in a slightly different pattern of activation within the same general regions (Woodruff et al., 2005). In addition to these areas, the right IFG was activated uniquely for the order task. This area has previously been shown to be involved in the selection of information from memory (Demb et al., 1995; Thompson-Schill et al., 1997; Miller & Cohen, 2001). If this selection process is operating in the present tasks, it makes sense that it would be more active for the order task. In the order task participants are shown three different numbers on each trial whereas in the magnitude task participants are presented a single number that is always compared to the same standard (65).

When considering the present results, it is important to note a study by Fulbright and colleagues (2003) in which fMRI data were collected while participants did a similar order task with numbers. In this study, participants saw three numbers (1-9) and had to indicate whether the numbers were in order (ascending or descending) or not. Behaviorally, participants showed DEs, taking a longer time when the numbers were closer together. There are, however, some differences between our study and theirs that could account for the different behavioral results. Besides the number task, a similar control task with shapes was intermixed throughout the experiment. Since assessing the size of shapes requires the processing of magnitude information, this may have biased participants towards a magnitude comparison strategy for the number task, leading to DEs. Also, their analyses collapsed across the direction of the stimulus, whereas in our study only forward trials were considered. Therefore, if RDEs were present for forward trials, they may have been difficult to detect when combined with the other trial types. Despite these behavioral differences, the neuroimaging data revealed a similar pattern of activation in the IPS, STG, insula, caudate, and IFG which is consistent with the present findings that these activations are not tied to the behavioral DE.

Conclusion

On the one hand, our data justify Jacob & Nieder's (2008) claim that magnitude and order information are "two sides of the same coin". Both types of information are likely represented along a spatial continuum in the IPS; the term 'magnitude' is used when the ends of that representation can be referred to as 'big' or 'small' whereas 'order' is used when those extreme values can be referred to as belonging to the 'beginning' or 'end' of the representation. This is consistent with work showing the involvement of similar parietal regions when accessing information about both spatial relations and temporal relations (which can be mapped spatially) from memory (Hayes et al., 2004). In addition to the similarity in how magnitude and order information are represented, the present results suggest that different processes are used when accessing this information. A comparison process is used for the magnitude task that results in DEs, and a scanning process is used in the order task which leads to RDEs. These RDEs for the order task were uniquely reflected by activation of the cerebellar vermis, which responded more to far than near trials. In addition, the involvement of regions associated with long-term memory retrieval (STG, insula, caudate) in both tasks suggests that besides accessing a mental number line, participants also retrieve facts from long-term memory when solving the problems. For the order task, the near>far comparison uniquely recruited the right IFG, which is probably related to the greater selection demands. Taken together these results provide new insights into the neural mechanisms underlying the representation and processing of magnitude and order information for numbers.

CHAPTER 5

General Discussion

This main goal of this work was to provide information about the representation and processing of order information in memory. This was done, in large part, by exploring the effects that distance between items have on the processing of order information. Previous work has mostly focused on what could be considered canonical DEs, in which it is easier to make decisions regarding order when the items span a greater distance (Moyer & Landauer, 1967). The present work makes a novel contribution by considering in more detail the underlying processes involved with other types of distance effects. Together, these different effects suggest that order information can be processed by multiple mechanisms; an estimation, scanning, and LTM-CM (See Appendix D for a list of publications/presentations based on these studies).

For example, in Study 1 with everyday routines, there were RDEs when the actions were from the middle of the routine, and DEs for trials with endpoint actions. This suggests that there are multiple ways to code and process temporal order information from everyday routines. Participants sometimes make use of specific temporal position information, and scan through the items from a routine in order. Other times participants make use of coarse temporal codes making it easier to decide the order of actions that are farther apart because they are more distinctly coded.

In Study 2, with numbers and months, in which the stimuli are well-learned ordered representations, the effects of distance interact with the two types of boundary crossing; decade crossing for numbers and year crossing for months. Figure 5.1 illustrates the processes involved with numbers for trials that cross and don’t cross a decade. Participants show RDEs when the numbers cross a decade, consistent with a scanning mechanism that accesses a mental number line, and takes longer with greater distance. When the numbers are within a decade, participants can make decisions about the order from the ones digits alone. Since order information about these single digit numbers (1-9) is well-learned, participants can retrieve the information from long-term memory independent of distance, making use of the LTM-CM. Additionally, participants may scan this single digit number line. The combination of the scanning and LTM-CM then leads to the absence of any significant effects of distance (though see further comments below).

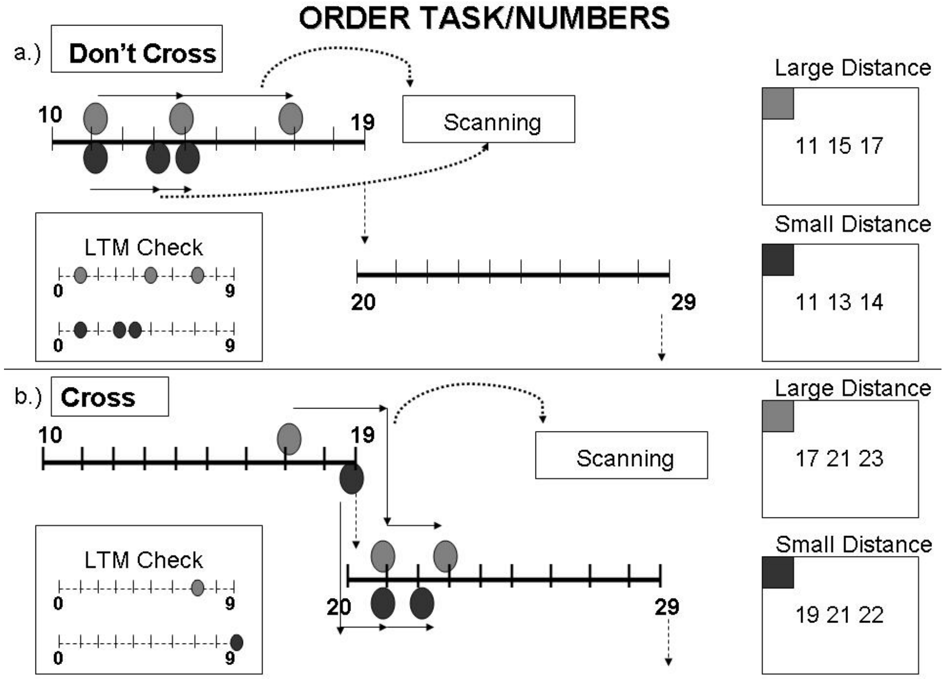


Figure 5.1 – Illustrates a model of number representation of order for forward trials. (a) For trials that do not cross a decade participants may decompose the numbers and focus on the ones digit. These facts about order of single digit numbers can then be retrieved from memory independent of distance (b) For trials that cross a decade, participants do not rely on long-term memory retrieval and scan through the representation, taking longer for greater distances.

Figure 5.2 shows how similar processes are involved when order for months is probed. As with the numbers, participants show RDEs for the cross trials taking longer when they span a greater distance. When the months are within the calendar year there is no effect of distance because these sequences are well learned so participants can make use of the LTM-CM. These similar behavioral effects suggest that these order processes are not specific to numbers, but apply to order information in general.

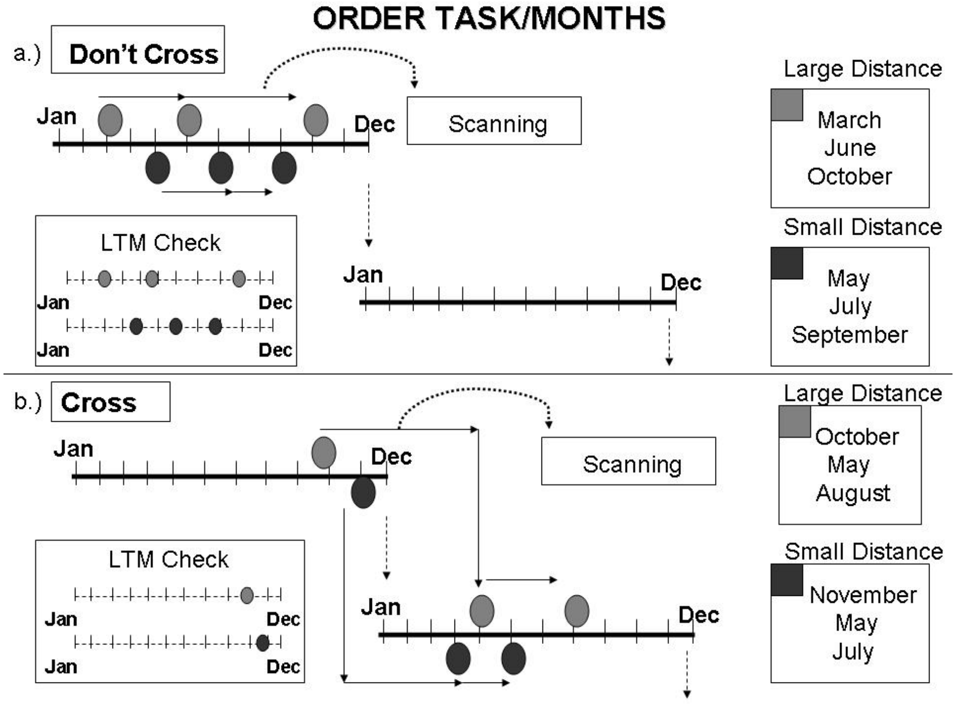


Figure 5.2 – Illustrates a model of the representation of order for months of the year for forward trials. (a) For trials that do not cross the year boundary (i.e., January) participants check order by using the LTM-CM (b) For trials that cross a year boundary that representation is insufficient to reach a decision, so participants scan through the months serially to decide about order.

Scanning/Estimation vs. Approximate/Exact

Based largely on patient work showing a dissociation in the types of performance deficits, Dehaene and colleagues (1997, 2003) have proposed two distinct number processing systems for which the present work can be mapped onto. Specifically, there are reports of one set of patients with deficits in exact calculation (true/false -- 2 + 2 = 5) but with maintained ability to approximate (true/false -- 2 + 2 = 9) and another set of patients showing the reverse of this; spared exact calculation with deficits in approximation (Dehaene & Cohen, 1997, Lemer et al., 2003). Therefore, it has been proposed that one system is responsible for exact calculation, which requires accessing specific arithmetic facts, and another that is used for approximation via analog representations of quantity.

In terms of the present study, the exact calculation system maps onto the LTM-CM. In the exact system, arithmetic facts about numerical order can be retrieved independent of the actual distance between numbers, which would lead to a lack of a distance effect as shown in Study 2. The approximate system best maps onto the estimation mechanism discussed in Study 1 since analog representations are presumably used for both numbers and everyday routines making comparisons more difficult when the stimuli are closer together. The present work would then also support the claim that scanning maps onto the approximate system as well, since this mechanism also involves accessing an analog mental number line. However, in this case, the information is accessed serially, which leads to reverse distance effects.

Neural Correlates of Order Processing

In addition to the behavioral data which have provided information about the underlying mechanisms involved in the processing of order information, this dissertation also contains fMRI data which offer insights into the neural correlates of order and magnitude processing for numbers. The major findings from Study 3 are consistent with previous work suggesting that the IPS represents a mental number line which is used to assess numerical magnitude information (Ansari et al., 2006; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Piazza et al., 2004; Pinel et al. 2001, 2004). However, the current work extends these findings by showing that these activations are not simply tied to the behavioral DEs. In addition, the present work suggests that the IPS does not simply represent magnitude information, but ordinal information as well. While this was recently proposed by Jacobs & Nieder (2008), the present findings make a much stronger case then previous work by dissociating the effects of distance from the neural activations.

The findings from Study 3 allow for speculation regarding the neural correlates of the different order mechanisms demonstrated in Studies 1 & 2. For example, it was proposed that the cerebellum, specifically the cerebellar vermis, may play an important role in the scanning mechanism due its unique activation for the order task RDEs. This is consistent with other work implicating this region in the processing of different types of order information such as sequential aspects of language as well as the temporal order of events (Fabbro et al. 2000; Ivry, 1997; Moretti et al., 2002).

Activations that uniquely corresponded to the DEs were found in more extensive parietal regions, in the IPS and SPL. Therefore it is possible that these regions not only represent magnitude and order information, but also make calculations via an estimation mechanism which leads to the DEs. This is consistent with Dehaene's (1992) triple-code model which proposes that in addition to the IPS, which represents magnitude in terms of a mental number line, other parietal regions are engaged in other aspects of number comparison tasks. For example, the posterior superior parietal system is thought to play a role in orienting verbal and visual attention when accessing numerical magnitude information (Dehaene et al., 2003), which could lead to the DEs.

With regards to the LTM-CM, Study 3 provides evidence that regions associated with long-term memory retrieval, the STG, insula, and caudate, are active for both order and magnitude tasks. These regions, therefore, likely comprise a network that functions as the LTM-CM discussed above. In addition to making calculations with a mental number line to assess order and magnitude, participants can directly retrieve the information from long-term memory. For the order task, this information is more likely available and accessed when the numbers are close together, which increases the chance they were encoded as a chunk of information. For the magnitude task, the LTM-CM is engaged on far trials when the stimuli can simply be coded as ‘big’ or ‘small’, making it unnecessary to consult the mental number line.

Lesion data also provide information about the neural correlates of these different mechanisms. For example, there is evidence for a double dissociation between order and magnitude processing. Turconi and Seron (2002) report a patient with bilateral parietal damage who shows deficits on order tasks (which comes next) but not on magnitude tasks (choose larger/smaller), while Delazar and Butterworth (1997) describe a patient with left frontal damage with deficits in processing magnitude (e.g., reverse distance effects in simple number comparison tasks) but preserved order processing (e.g., answering what comes next). These studies suggest that parietal lobe is more involved in order processing. However, these findings are somewhat equivocal in that other patient work (Lemer et al., 2003) as well as a study using rTMS (Sandrini, 2004) reveal deficits specific to magnitude comparison tasks with parietal lesions. Therefore, taken together these studies provide evidence for the parietal lobe’s involvement in both order and magnitude processing. Additionally, the study by Lemer and colleagues (2003) support the conclusion drawn in Study 3 for the involvement of temporal regions in the LTM-CM, in that left temporal lesions were shown to disrupt the exact number system, while leaving the approximate intact.

Future Directions

The work presented thus far suggests that there are two common mechanisms that process order and magnitude information. Studies 1 and 3 show that an estimation mechanism, which leads to DEs, can operate for both order and magnitude information. In addition, the behavioral and neuroimaging work suggest that a LTM-CM can be used to process both types of information. Future work could be done to investigate whether it is possible to show RDEs for a magnitude comparison. One way to test this would be adapt the order task used in Study 2a & 3 by using stimuli that need to be ordered by features such as size or brightness, which reflect magnitude. This study may provide evidence that it is possible to scan magnitude information, or conversely, show that scanning is an order-specific process.

Another continuation of this work would be to compare the neural activation from an order task with months to that of numbers. This would provide information regarding the neural specificity of number processing. There was a recent study by Kadosh and colleagues (2006) which showed activations in the left IPS for number comparisons that was not seen for physical size and brightness comparisons. The authors, therefore, claim that there are specialized regions in the IPS for the processing of numerical information. There is, however, still the possibility that this region may not be number specific, but rather generally responsive to symbols that represent specific position information. Therefore, common IPS activation for numbers and months would be consistent with the hypothesis that this region's function is not specific to number processing, but rather, order processing in general.

Conclusion

The ability to not just encode information in memory, but to encode the sequential relations between different pieces of information, is fundamental to human cognition. Without this ability we would be unable to complete even the simplest everyday tasks. The first study provides new details about how memory for routine events is represented and processed. Specifically, it was shown that memory for routine events consists of both the specific position information of the constituent actions as well as a more general "gist" information about when the events occur in relation to each other.

Besides the temporal order information from everyday routines, sequential information is also explicitly learned in the form of lists from a very young age. For example, we learn to count, recite the alphabet, and know the order of the days of the week and the months of the year. The second part of this dissertation shows that the same processes used for both everyday routines are also utilized for these well-learned sequences. By focusing on numbers it was also shown that some of these processes, like estimation and long-term memory retrieval, can also be used to process magnitude information. This work suggests that just as magnitude information can be represented along a spatial continuum, so too, can order information for everyday events and well-learned lists like numbers and months. Specifically, the findings from Study 3 suggest that the IPS plays an important role in representing a mental number line that can be used to access both order and magnitude information for numbers.

Taken together, this dissertation therefore provides a number of new insights on how order information is both represented and processed in memory.

APPENDICES

APPENDIX A

Decade Crossing in Study 3

Although Study 2 showed an interaction between decade crossing and distance, the analyses presented in Study 3 collapsed across the decade crossing variable, focusing on just whether the trials were near or far. Below I provide the rationale for excluding decade crossing in Study 3 and provide additional analyses that consider the effects of decade crossing.

Figure A.1 shows that the behavioral data from the order task in Study 3 are consistent with those from Study 2. There is a RDE when the trials cross a decade and no significant effect of distance when the trials do not cross a decade (see Figure 5.3). This interaction of distance by decade crossing was significant ($F(1,14) = 5.065$, $p = .032$). There were also significant main effects for distance ($F(1, 14) = 9.39$, $p = .0008$) and decade crossing ($F(1, 14) = 32.07$ $p < .0001$).

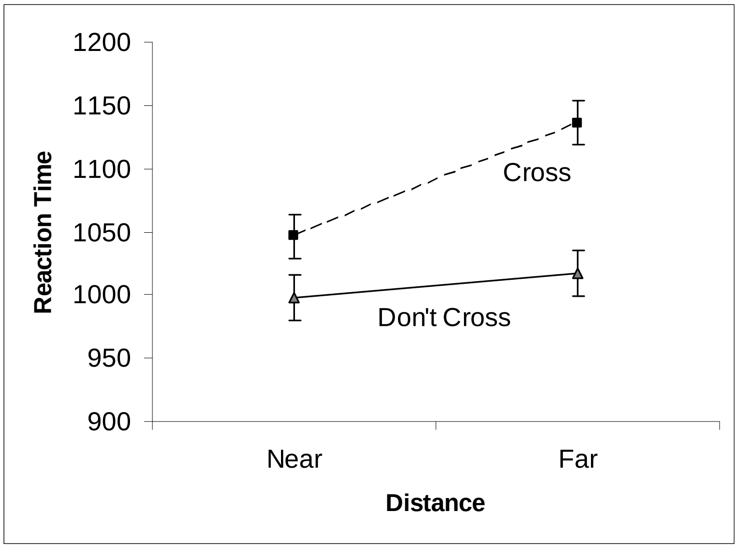


Figure A.1 The interaction of distance and decade crossing for reaction times with numbers in the forward direction. There is no DE when the numbers are in the same decade, and a significant RDE when the numbers cross decades.

Despite these behavioral results that replicate the findings from Study 2, there were a number of reasons for excluding this from the main text of Study 3. The first reason was based on the overall goal of Study 3, which was to compare an order task showing RDEs to a magnitude task showing DEs. While it would seem as though this comparison should only involve the cross trials (which show strong RDEs), closer analyses reveal scanning for the don't cross trials as well. Even though there is not a significant RDE for the don't cross trials in Study 2a and in Study 3 individually, a majority of the participants have a tendency to show RDEs (Study 2a: 13/19; Experiment 3: 11/14) and when these two studies are combined, the RDEs becomes significant (F(1,33) = 4.59, p = .03) This suggests that there are simply weaker RDEs for the don't cross trials. Therefore, in addition to a LTM-CM, it is also possible that participants decompose the numbers and can scan these single digit numbers faster than two-digit numbers. Since the months can not be decomposed, participants rely on the LTM-CM, as evidenced by the flat distance function (don’t cross near = 2096 ms, don’t cross far = 2098 ms).

Given that there are RDEs for the don’t cross trials, another reason for collapsing across the decade crossing variable was to increase the power to detect significant effects in the fMRI data. By collapsing over the decade crossing variable we were able to estimate the models using twice as many trials, thus greatly increasing the signal to noise ratio.

An additional reason for collapsing over the decade crossing variable had to do with the size of the distance effects. When collapsing over the decade crossing variable, the DEs and RDEs become more equivalent (~50ms). This helps rule out the possibility that the unique activations for each of the task are simply due to differences in the size of the distance effects.

A final reason for collapsing over the decade crossing variable has to do with the imaging data for cross and don’t cross trials. There were no activations unique to the cross and don’t cross conditions that index RDEs. In other words, there were no unique activations when comparing the cross far>near and don’t cross far>near contrasts. The similarity in neural processing further justifies the decision to combine the cross and don’t cross trials to investigate RDEs in Study 3.

APPENDIX B

Whole brain analyses from Study 3

Below are some additional whole brain fMRI results for the 4 contrasts of interest (magnitude near>far, magnitude far>near, order near>far, order far>near).

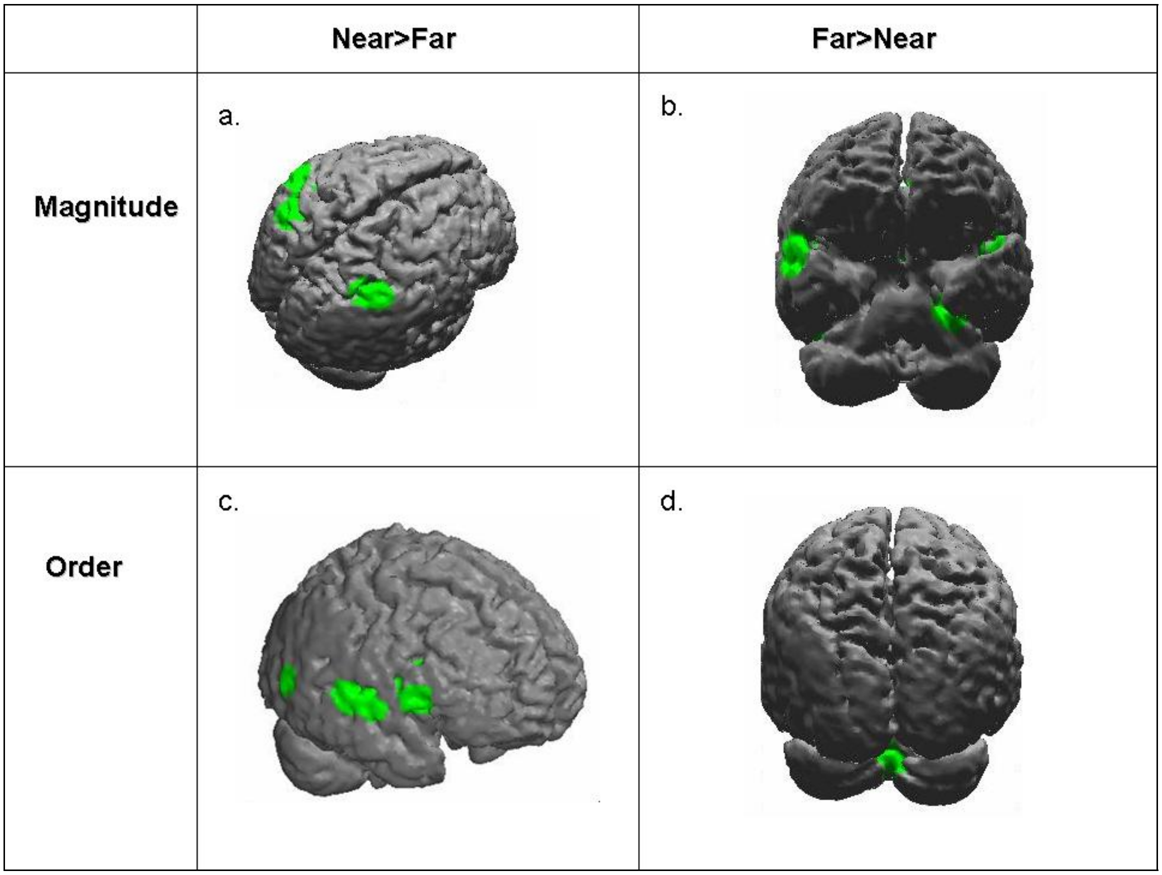
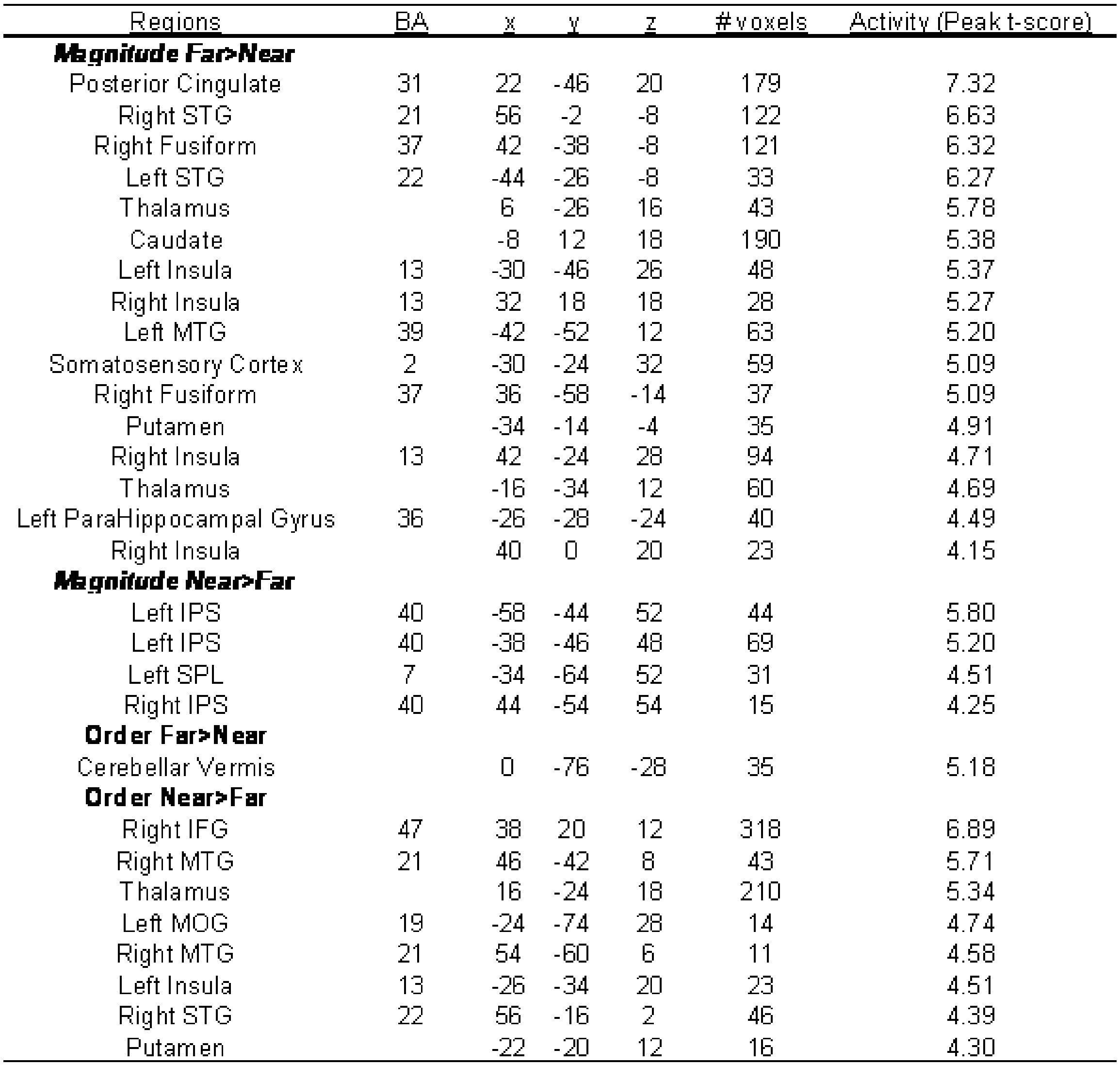


Figure B.1. Whole brain activations from the individual task analyses (a) magnitude near>far (b) magnitude far>near (c) order near>far (d) order far>near (where p <.001 and >10 contiguous voxels).

Table B.1 Displays information regarding the specific clusters from the individual task analyses



Regions	BA	x	y	z	# voxels	Activity (Peak t-score)
Magnitude Far>Near						
Posterior Cingulate	31	22	-46	20	179	7.32
Right STG	21	56	-2	-8	122	6.63
Right Fusiform	37	42	-38	-8	121	6.32
Left STG	22	-44	-26	-8	33	6.27
Thalamus		6	-26	16	43	5.78
Caudate		-8	12	18	190	5.38
Left Insula	13	-30	-46	26	48	5.37
Right Insula	13	32	18	18	28	5.27
Left MTG	39	-42	-52	12	63	5.20
Somatosensory Cortex	2	-30	-24	32	59	5.09
Right Fusiform	37	36	-58	-14	37	5.09
Putamen		-34	-14	-4	35	4.91
Right Insula	13	42	-24	28	94	4.71
Thalamus		-16	-34	12	60	4.69
Left ParaHippocampal Gyrus	36	-26	-28	-24	40	4.49
Right Insula		40	0	20	23	4.15
Magnitude Near>Far						
Left IPS	40	-58	-44	52	44	5.80
Left IPS	40	-38	-46	48	69	5.20
Left SPL	7	-34	-64	52	31	4.51
Right IPS	40	44	-54	54	15	4.25
Order Far>Near						
Cerebellar Vermis		0	-76	-28	35	5.18
Order Near>Far						
Right IFG	47	38	20	12	318	6.89
Right MTG	21	46	-42	8	43	5.71
Thalamus		16	-24	18	210	5.34
Left MOG	19	-24	-74	28	14	4.74
Right MTG	21	54	-60	6	11	4.58
Left Insula	13	-26	-34	20	23	4.51
Right STG	22	56	-16	2	46	4.39
Putamen		-22	-20	12	16	4.30

APPENDIX C

Additional Figures and Tables from Study 3

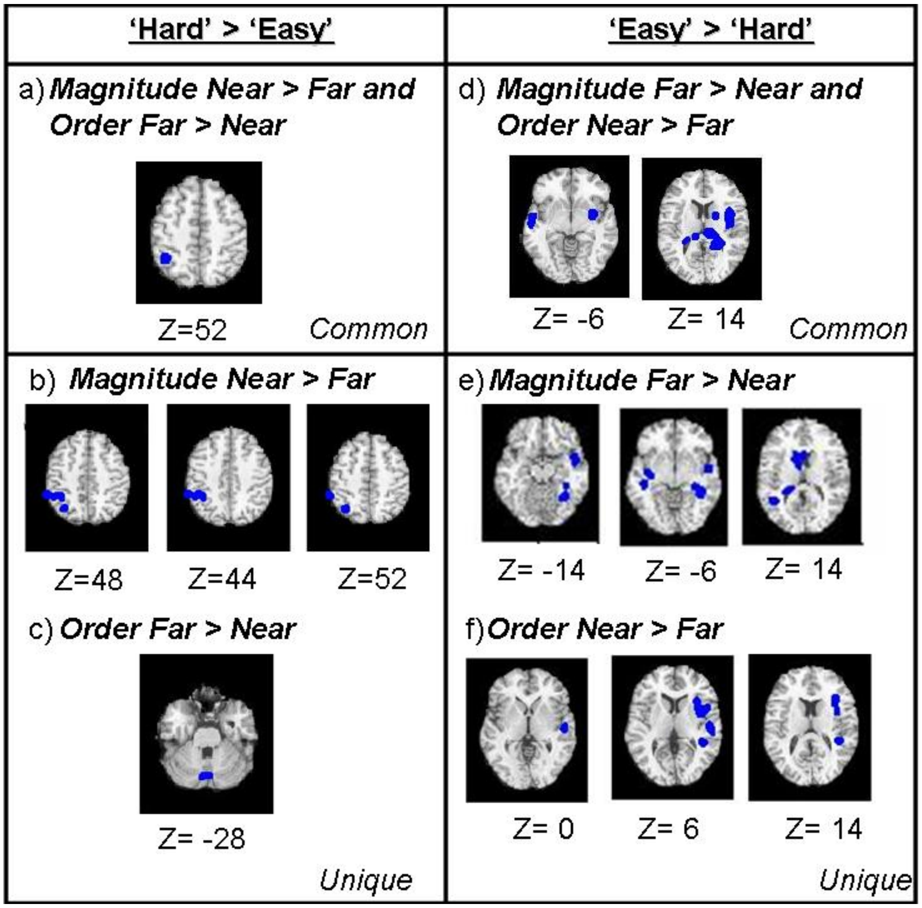


Figure C.1. The common and unique activations from Study 3 shown with a slice view.

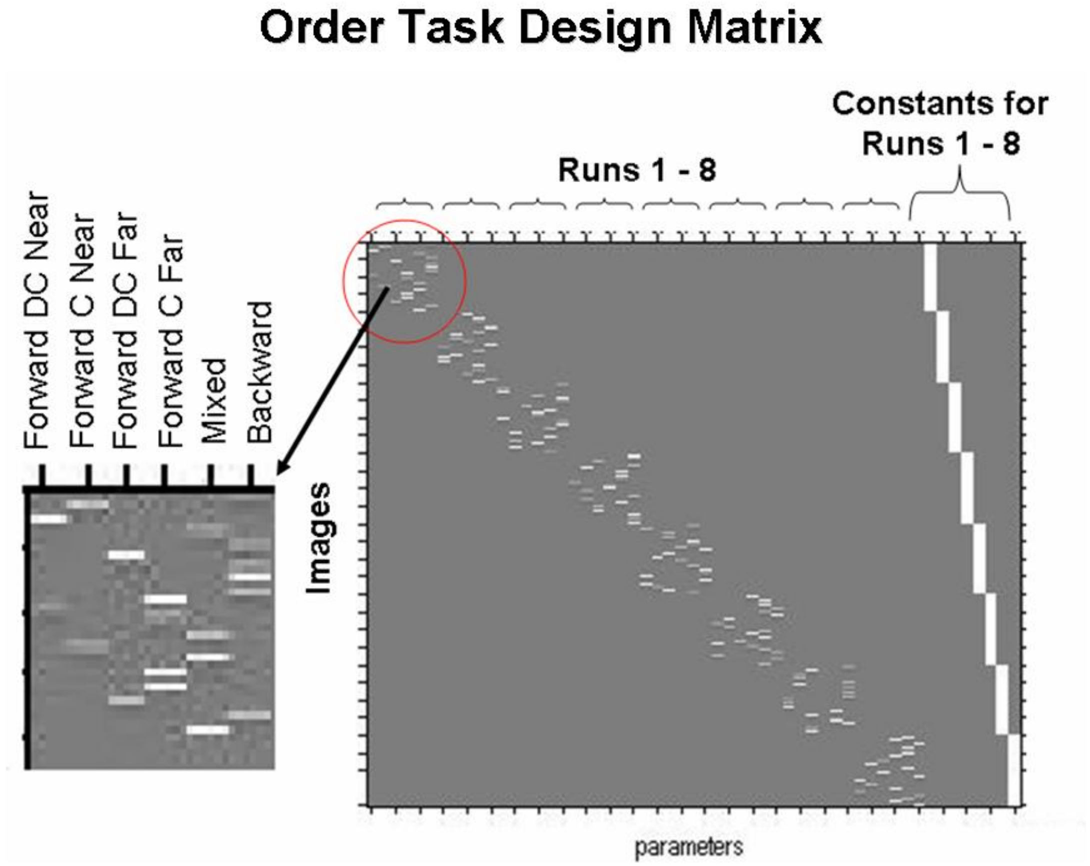


Figure C.2. A design matrix for the order task.

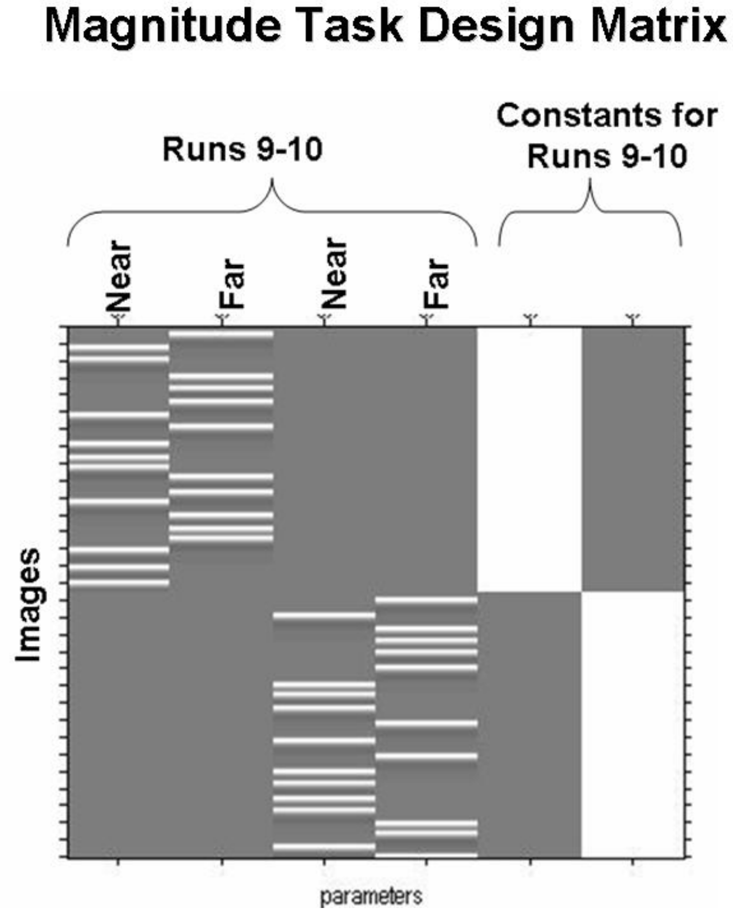
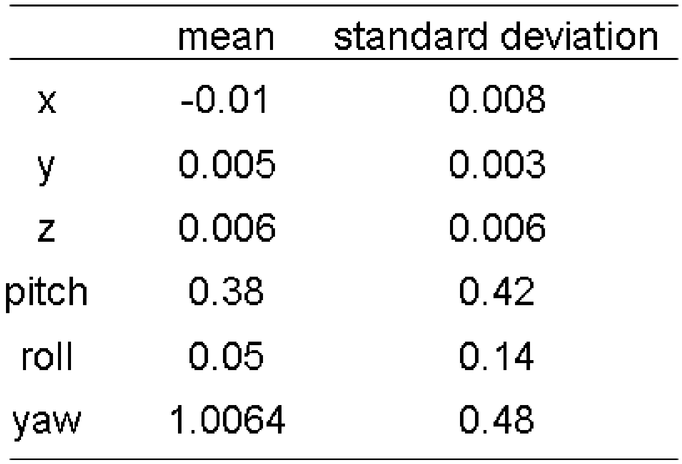


Figure C.3. A design matrix for the magnitude task.

Table C.1. Displays the means and standard deviations of the of the six motion parameters in mm.



	mean	standard deviation
x	-0.01	0.008
y	0.005	0.003
z	0.006	0.006
pitch	0.38	0.42
roll	0.05	0.14
yaw	1.0064	0.48

APPENDIX D

A List of Publications and Presentations from Studies 1-3

Franklin, M.S., Jonides, J. (submitted) Order and magnitude share a common representation in parietal cortex

Franklin, M.S., Jonides, J., Smith, E.E., (submitted). A New Perspective on Number Representation: Evidence from Order Judgments.

Franklin, M.S., Smith, E.E., Jonides, J. (2007). Distance effects in memory for sequences: Evidence for estimation and scanning processes. *Memory*, 15(1), 104-116.

Franklin, M.S., Jonides, J., Smith, E.E. (November, 2006). Distance effects in a task with numbers and months. A poster presented at the meeting of the Psychonomics Society, Houston, TX.

Franklin, M.S., Smith, E.E, Jonides, J., Grossman, M., Ananti, S. (April, 2005). A comparison of frontal patients and controls on a sequencing task. Presented at Cognitive Neuroscience Society, New York.

Franklin, M.S., Smith, E.E, Jonides, J. (November, 2004). Distance effects in a sequencing task. A poster presented at the meeting of the Psychonomics Society, Minneapolis, Minnesota.

BIBLIOGRAPHY

Ansari, D., Fugelsang, J. A., Dhital, B., & Venkatraman, V. (2006a). Dissociating response conflict from numerical magnitude processing in the brain: An event-related fMRI study, *NeuroImage*, 32(2), 799-805.

Ansari, D., Dhital, B., & Siong, S. C. (2006b). Parametric effects of numerical distance on the intraparietal sulcus during passive viewing of rapid numerosity changes. *Brain research*, 1067(1), 181-8.

Abbott,V., Black, J.B., & Smith, E.E. (1985). The representation of scripts in memory. *Journal of Memory and Language*, 24, 179-199.

Ashcraft, M. H. (1992). Cognitive arithmetic: A review of data and theory. *Cognition, 44,* 75-106.

Banks, W.P. (1977). Encoding and processing of symbolic information in comparative judgments. *The Psychology of Learning and Motivation*, 11, 101–159.

Barsalou, L., & Sewell, D. (1985). Contrasting the Representation of Scripts and Categories. *Journal of Memory and Language*, 24, 646–665.

Bower, G.H., Black, J.B., & Turner, T.J. (1979). Scripts in memory for text. *Cognitive Psychology*, 11, 177 - 220.

Black, J. B. & Bower, G. H. (1980). Episodes as chunks in narrative memory. *Journal of Verbal Learning and Verbal Behavior, 18,* 309-318.

Brannon, E. M., and Terrace, H. S. (1998). Ordering of the numerosities 1-9 by monkeys. *Science*. 282, 746-748.

Brannon, E.M., & Van de Walle, G. (2001) Ordinal numerical knowledge in young children. *Cognitive Psychology*, 43, 53-81.

Brysbaert, M. (1995). Arabic number reading: On the nature of the numerical scale and the origin of phonological recoding. *Journal of Experimental Psychology: General*, 124, 434–452.

Cantlon, J., & Brannon, E.M. (2006). Shared system for ordering small and large numbers in monkeys and humans. *Psychological Science*, 17(5), 401-406.

Carey, S. (2004). Bootstrapping & the origin of concepts. *Daedalus*, 59-68.

Dean, G.M., Dewhurst, S.A., Morris, P.E., & Whittaker, A. (2005). Selective interference with the use of visual images in the symbolic distance paradigm. *Journal of Experimental Psychology: Learning, Memory & Cognition*, 31, 1043-1068.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance* 16, 626-641.

Dehaene, S., & Cohen, L. (1991). Two mental calculation systems: a case study of severe acalculia with preserved approximation. *Neuropsychologia*, 29(11), 1045-54**.**

Dehaene,S., & Changeux,J.-P. (1993). Development of elementary numerical abilities: A neuronal model. *Journal of Cognitive Neuroscience*, 5, 390-407.

Dehaene, S., & Cohen, L. (1997). Cerebral pathways for calculation: double dissociation between rote verbal and quantitative knowledge of arithmetic, *Cortex*, 33(2), 219-50.

Dehaene, S., Dehaene-Lambertz, G., & Cohen, L. (1998). Abstract representations of numbers in the animal and human brain. *Trends in Neuroscience*, 21, 355-361.

Dehaene**,** S. (2003). The neural basis of the Weber-Fechner law: A logarithmic mental number line. *Trends in Cognitive Sciences*, 7(4), 145-147

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Journal of Cognitive Neuropsychology*, 20, 487–506.

Delazer, M., & Butterworth, B. (1997). A dissociation of number meanings. *Cognitive Neuropsychology*, 14(4), 613-636.

Demb, J. B., Desmond, J. E., Wagner, A. D., & Vaidya, C. J. (1995). Semantic encoding and retrieval in the left inferior prefrontal cortex: A functional MRI study of task difficulty and process specificity., *Journal of Neuroscience*, 15(9), 5870-5878.

Ebenholtz, S. M. (1963). Serial learning: Position learning and sequential association. *Journal of Experimental Psychology*, 70, 176-181.

Fabbro, F., Moretti, R., & Bava, A. (2000). Language impairments in patients with cerebellar lesions. *Journal of Neurolinguistics* 13, 173-188.

Fan, J., Flombaum, J. I., McCandliss, B. D., Thomas, K. M., & Posner, M. I. (2003). Cognitive and brain consequences of conflict, *NeuroImage*, 18(1), 42-57.

Feigenson, L., Dehaene, S., & Spelke, E.S. (2004). Core systems of number. *Trends in Cognitive Sciences*, **8**, 307–314.

Fias, W., Lammertyn, J., Caessens, B., & Orban, G. A. (2007). Processing of abstract ordinal knowledge in the horizontal segment of the intraparietal sulcus, *The Journal of neuroscience : the official journal of the Society for Neuroscience*, 27(33), 8952-6.

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, P., & Orban, G. A. (2003). Parietal representation of symbolic and nonsymbolic magnitude, *Journal of cognitive neuroscience*, 15(1), 47-56.

Foss, C. L. & Bower, G. H. (1986). Understanding actions in relation to goals. In N. E. Sharkey (Ed.), Advances in cognitive science 1, (94-124). Chichester: Ellis Horwood.

Franklin, M. S., Jonides, J., & Smith, E. E. (2006). *Distance Effects in an Order Task with Numbers and Months.* Paper presented at the Psychonomic Society, Houston, TX.

Franklin, M.S., Smith, E.E., Jonides, J. (2007). Distance effects in memory for sequences: Evidence for estimation and scanning processes. *Memory*, 15(1), 104-116.

Franklin, N., & Bower, G. (1988). Retrieving Actions from Goal Hierarchies. *Bulletin of the Psychonomic Society*, 26, 15–18.

Friederici, A. D., Rüschemeyer, S., Hahne, A., & Fiebach, C. J. (2003). The role of left inferior frontal and superior temporal cortex in sentence comprehension: localizing syntactic and semantic processes, *Cerebral cortex (New York, N.Y. : 1991)*, 13(2), 170-7.

Friedman, W.J. (1983). Image and verbal processes in reasoning about the months of the year. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 9, 650-666.

Fulbright, R. K., Manson, S. C., Skudlarski, P., Lacadie, C. M., & Gore, J. C. (2003). Quantity determination and the distance effect with letters, numbers, and shapes: a functional mr imaging study of number processing, *American journal of neuroradiology*, 24(2), 193-200.

Galambos, J. (1983). Normative studies of six characteristics of our knowledge of common activities. *Behavior Research Methods & Instrumentation*, 15, 3, 327-340.

Galambos, J. A. & Rips, L. J. (1982). Memory for routines. *Journal of Verbal Learning and Verbal Behavior*, 21, 260–281.

Geary, D. C. (1993). Mathematical disabilities: Cognitive, neuropsychological, and genetic components. *Psychological Bulletin*, 114, 345-362.

Gallistel,C.R., & Gelman,R. (1992). Preverbal and verbal counting and computation. *Cognition*, 44, 43-74.

Gallistel, C. R. and Gelman, R. (2000). Non-verbal numerical cognition from reals to integers. *Trends in Cognitive Sciences*, 4(2), 59-65.

Gélinas, C.S., & Desrochers, A. 1993. Positive and negative instructions in symbolic paired comparisons with the months of the year. *Psychological Research*, 55(1), 40-51.

Goldman, A. I. (2002). Simulation theory and mental concepts. In J. Dokic and J. Proust (eds.), Simulation and Knowledge of Action (1-19). Amsterdam: John Benjamins.

Hayes, S. M., Ryan, L., Schnyer, D. M., & Nadel, L. (2004). An fMRI study of episodic memory: retrieval of object, spatial, and temporal information, *Behavioral neuroscience*, 118(5), 885-96.

Hesslow, G. (2002). Conscious thought as simulation of behaviour and perception. *Trends in Cognitive Sciences*, 6(6), 242-247.

Ivry, R. (1997). Cerebellar timing systems, *International review of neurobiology*, 41, 555-73.

Jacob, S. N., & Nieder, A. (2008). The abc of cardinal and ordinal number representations, *Trends in cognitive sciences*, 12(2), 41-3.

Jenkinson, M., Bannister, P., Brady, M., & Smith, S. (2002). Improved optimization for the robust and accurate linear registration and motion correction of brain images, *NeuroImage*, 17(2), 825-841.

Jou, J. (2003). Multiple number and letter comparison: Directionality and accessibility in numeric and alphabetic memories. *American Journal of Psychology*, 116, 543–579.

Jung-Beeman, M., Bowden, E. M., Haberman, J., Frymiare, J. L., Arambel-Liu, S., Greenblatt, R., et al. (2004). Neural activity when people solve verbal problems with insight, *PLoS biology*, 2(4), E97.

Kaufmann, L., Koppelstaetter, F., Delazer, M., Siedentopf, C., Rhomberg, P., Golaszewski, S., et al. (2005). Neural correlates of distance and congruity effects in a numerical stroop task: an event-related fmri study, *NeuroImage*, 25(3), 888-98.

Kotz, S. A., Cappa, S. F., von Cramon, D. Y., & Friederici, A. D. (2002). Modulation of the lexical-semantic network by auditory semantic priming: an event-related functional MRI study, *NeuroImage*, 17(4), 1761-72.

Krueger, L. E. (1989). Reconciling Fechner and Stevens: Toward a unified psychophysical law. *Behavioral and Brain Sciences*, 12(2), 251-320.

Le Corre, M., & Carey, S. (in press). One, two, three, four, nothing more: An investigation of the conceptual sources of the verbal counting principles. *Cognition*.

Lemer, C., Dehaene, S., Spelke, E., & Cohen, L. (2003). Approximate quantities and exact number words: Dissociable systems, *Neuropsychologia*, 41(14), 1942-58.

Lewandowsky, S., & Li, S.-C. (1994). Memory for serial order revisited. *Psychological Review*, *101*, 539-543.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review, 1*, 476-490.

Marshuetz, C., Smith, E.E., Jonides, J., DeGutis, J., & Chenevert, T.L. (2000). Order information in working memory: fMRI evidence for parietal and prefrontal mechanisms. *Journal of Cognitive Neuroscience*, 12(2), 130–144.

Marshuetz C. (2005). Order information in working memory: An integrative review of evidence from brain and behavior. *Psychological Bulletin*, 131, 323–339.

Marshuetz, C . Reuter-Lorenz, P.A., Smith, E.E. Jonides, J., Noll, D.C., (2006). Working memory for order and the parietal cortex: An event-related fMRI study. *Neuroscience*, 139, 311-316.

McCloskey, M. (1992). Cognitive mechanisms in numerical processing: evidence from acquired dyscalculia.*Cognition*, 44, 107-157.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function, *Annual review of neuroscience*, 24, 167-202.

Moretti, Bava, Torre, Antonello, & Cazzato. (2002). Reading errors in patients with cerebellar vermis lesions, *Journal of Neurology*, 249(4), 461-468.

Moyer, R. S. (1973). Comparing objects in memory: Evidence suggesting an internal psychophysics. *Perception & Psychophysics*, 13, 180-184.

Naccache, L., & Dehaene, S. (2001). The priming method: Imaging unconscious repetition priming reveals an abstract representation of number in the parietal lobes, *Cerebral cortex*, 11(10), 966-74.

Nottenburg, G. & Shoben, E. J. (1980). Scripts as linear orders. *Journal of Experimental Social Psychology* 16: 329-347.

Nuerk, H.-C., Weger, U. & Willmes, K. Decade breaks in the mental number line? Putting the tens and units back in different bins. *Cognition*, 82, B25-B33.

Nuerk, H.-C., Weger, U. & Willmes, K. (2004). On the perceptual generality of the unit-decade compatibility effect. *Experimental Psychology, 51,* 72-79.

Nuerk, H.-C. & Willmes, K. (2005). On the magnitude representation of two-digit numbers. *Psychology Science: Special Issue Brain and Number, 42*, 52-72.

Osmon, D. C., Smerz, J. M., Braun, M. M., and Plambeck, E. (2006). Processing abilities associated with math skills in adult learning disability. *Journal of Clinical and Experimental Neuropsychology*, 28(1), 1-12.

Oppenheim, A. V., & Schafer. (1999). *Discrete-time signal processing* (2nd ed.). Upper Saddle River, NJ: Prentice Hall.

Parkman, J. M. (1971). Temporal aspects of digit and letter inequality judgments. *Journal of Experimental Psychology*, 91, 191–205.

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., & Dehaene, S. (2004). Tuning curves for approximate numerosity in the human intraparietal sulcus, *Neuron*, 44(3), 547-55.

Piazza, M., Pinel, P., Le Bihan, D., & Dehaene, S. (2007). A magnitude code common to numerosities and number symbols in human intraparietal cortex, *Neuron*, 53(2), 293-305.

Pinel, P., Le Clec'H, G., van de Moortele, P.F., Naccache, L., Le Bihan, D., & Dehaene, S. (1999). Event-related fMRI analysis of the cerebral circuit for number comparison. *NeuroReport* 10, 1473–1479.

Pinel, P., Dehaene, S., Riviere, D., & Le Bihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *Neuroimage,* 14, 1013–1026.

Pinel, P., Piazza, M., Le Bihan, D., & Dehaene, S. (2004). Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. Neuron, 41, 983–993.

Presenti, M., Thioux, M., Seron, X., De Volder, A. (2000). Neuroanatomical substrates of arabic number processing, numerical comparison, and simple addition: a PET study**.** *Journal of Cognitive Neurosci*ence, 12, 461 –479.

Rissman, J., Eliassen, J. C., & Blumstein, S. E. (2003). An event-related fMRI investigation of implicit semantic priming, *Journal of cognitive neuroscience,* 15(8), 1160-75.

Rosenbaum, D., Inhoff, A., & Gordon, A. (1984). Choosing between movement sequences: A hierarchical editor model. Journal of Experimental Psychology: General, 113(3), 372-393.

Rosselli M, Matute E, Pinto N, Ardila A. (2006). Memory abilities in children with subtypes of dyscalculia. *Developmental Neuropsychology,* 30(3), 801-18.

Rumelhart, D.E. (1977). D.E. Rumelhart, Understanding and summarizing brief stories. In: D. LaBerge and J. Samuels, Editors, *Basic processes in reading and comprehension*, Lawrence Erlbaum Associates, Hillsdale, NJ.

Sandrini, M., Rossini, P. M., & Miniussi, C. (2004). The differential involvement of inferior parietal lobule in number comparison: a rTMS study, *Neuropsychologia*, 42(14), 1902-9.

Schulze, K. G., Schmidt-Nielsen, A., Achille, L. B. (1991). Comparing three numbers: The effect of number of digits, range, and leading zeros. *Bulletin of the Psychonomic Society*, 29(4), 361-364.

Seymour, P.H.K. (1980a). Internal representation of the months: An experimental analysis of spatial forms. *Psychological Research*, 42, 255-273.

Seymour, P.H.K. (1980b). Semantic and structural coding of the months. *British Journal of Psychology*, 71, 371-393.

Shalev, R.S., Manor, O., & Gross-Tsur, V. (2005). Developmental Dyscalculia: a prospective six-year follow up. *Developmental Medicine and Child Neurology*, 47, 121-125.

Sirigu, A., Zalla, T., Pillon, B., Grafman, J., Agid, Y., & Dubois, B. (1996). Encoding of sequence and boundaries of scripts following prefrontal lesions. *Cortex*, 32, 297–310.

Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: a reevaluation, *Proceedings of the National Academy of Sciences of the United States of America*, 94(26), 14792-7.

Turconi, E., & Seron, X. (2002). Dissociation between order and quantity meaning in a patient with Gerstmann syndrome. *Cortex*, 38(5), 911-914.

Turconi, E., Campbell, J. I. D., & Seron, X. (2006). Numerical order and quantity processing in number comparison. *Cognition*, 98, 273-285.

Van Petten, C., & Luka, B. J. (2006). Neural localization of semantic context effects in electromagnetic and hemodynamic studies, *Brain and language*, 97(3), 279-93.

Verguts, T., Fias, W., & Stevens, M. (2005). A model of exact small number representation. *Psychonomic Bulletin & Review*, 12, 66-80.

Verguts, T., & Van Opstal, F**.** (2005). Dissociation of the distance effect and size effect in one-digit numbers. *Psychonomic Bulletin & Review*, 12, 925-930.

Wager, T. D., Sylvester, C. C., Lacey, S. C., Nee, D. E., Franklin, M., & Jonides, J. (2005). Common and unique components of response inhibition revealed by fMRI, *NeuroImage*, 27(2), 323-40.

Welford, A. T. (1960). The measurement of sensory-motor performance: Survey and reappraisal of twelve years progress. *Ergonomics, 3,* 189-230.

Whalen, J., Gallistel, C. R., and Gelman, R. (1999). Nonverbal counting in humans: The psychophysics of number representation. *Psychological Science*, 10 (2), 130-137.

Wood, G., Nuerk, H., & Willmes, K. (2006). Neural representations of two-digit numbers: A parametric fMRI study, *NeuroImage*, 29(2), 358-67.

Woodruff, C. C., Johnson, J. D., Uncapher, M. R., & Rugg, M. D. (2005). Content-specificity of the neural correlates of recollection, *Neuropsychologia*, 43(7), 1022-32.

Wynn, K. (1998) Psychological foundations of number: Numerical competence in human infants. *Trends in Cognitive Science*, 2, 296–303.

Young, R. K. (1962). Tests of three hypotheses about the effective stimulus in serial learning. *Journal of Experimental Psychology*, 63, 307-313.

Zacks, J., & Tversky, B. (2001). Event structure in perception and conception. Psychological Bulletin, 127, 3-21.

Zacks, J., Tversky, B., & Iyer, G. (2001). Perceiving, remembering and communicating structure in events. *Journal of Experimental Psychology: General*, 136, 29-58.