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# Modelling the Category-Order Effect with an Oscillator-Based Connectionist Network

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## Abstract

Numerous factors interact to affect a participant's ability to encode and recall information. One example of this interaction is known as the category-order effect (COE; Brooks and Watkins, 1990). The present study models earlier work performed by the authors (Schoenherr & Thompson, 2008) with an oscillator-based model of memory (Brown et al., 2000). The OSCillator-based Associative Recall (OSCAR) network developed by Brown et al. (2000) was adapted to examine the role that attention plays in the COE. A series of simulations demonstrate that both the differential allocation of attention to items, as well as the strength of items stored in memory, independently contribute to the COE. Further lines of experimental inquiry are also discussed.

**Keywords:** category-order effect; OSCAR; list recall; memory; lexicality; working memory

## Introduction

Early studies of memory capacity observed a central distinction between the items being retained and their order of presentation and recall (Healy, 1974; Lashley, 1951). More recently, the interaction of item and position in a sequence have been examined in terms of the category-order effect (Brooks & Watkins, 1990). Brooks and Watkins (1990) defined the category-order effect in terms of an improvement in list recall performance when items from a relatively smaller, homogeneous category are presented prior to a comparatively larger, heterogeneous category (Brooks & Watkins, 1990; Greene & Lasek, 1994). Later work by Schoenherr & Thomson (2008) expanded this notion, finding category-order effects when stimuli from a more salient category preceded those from the less salient category, regardless of category size.

Extending our previous work on the category-order effect (Schoenherr & Thomson, 2008), the present study uses an OSCillator-based Associative Recall (OSCAR) network developed by Brown et al. (2000) to examine the contributions of stimulus presentation order and readily distinguishable categories that underlie the category-order effect (Brooks & Watkins, 1990; Greene & Lasek, 1994).

## The Category-Order Effect

Category-order effects have been revealed across a wide range of category properties (e.g. differential frequency, lexicality, and numerals) and are present during both forward and backward recall of list stimuli (Brooks &

Watkins, 1990; Greene & Lasek, 1994; Schoenherr & Thomson, 2008). Still, the robustness of the category-order effect is not unquestionable: the effect can be eliminated by inhibiting the consolidation of information by decreasing presentation rates, through articulatory suppression and through the reduction of available attentional resources (Greene & Lasek, 1994; for a more complete discussion of the influences on category-order effects, see Schoenherr & Thomson, 2008).

## Models of Human Memory

To better understand the processes underlying category-order effects, it is important to identify several models of human memory and identify which provides a plausible explanation of the effects. Three models proposed different underlying mechanisms to describe serial position findings in the memory literature (see reviews in Brown et al., 2000; Henson, 1998).

*Chaining Theory* (Ebbinghaus, 1964) postulates associations between neighbouring elements such that each element is the cue for the subsequent items in memory. Once retrieval is initiated, each item should activate its neighbour in a series of sequential pairwise associations until all items are retrieved. In this model, order information corresponds to the associations between items in memory. A limitation of chaining models is that high item-similarity (including item repetition in the extreme example) causes much higher than expected confusion during recall because highly-similar associations have similar retrieval cues.

*Positional Theory* (Conrad, 1965) assumes that, after encoding, successive items are stored in ordered slots (i.e. bins). In contrast to chained associations, there is no individuated storage of item and order information: order (re: bins) is an implicit mechanism which cues retrieval of item information. Two difficulties of this theory are that there is no plausible explanation of how bins are organized, and theoretically this theory claims there should be no serial position errors.

*Ordinal Theory* (e.g., Estes, 1972) assumes that the position of a list item is stored as a relative value along a continuous property of the items. In the case of memory, the relative strength of the memory trace is used to derive positional information. An advantage of ordinal models is that no explicit positional information need be encoded. The main limitation in ordinal models is that the middle

elements in a list cannot be recalled before prior elements (as prior elements will have a stronger memory trace).

To account for the aforementioned limitations, the general processes implicated in Ordinal Theory were expanded to account for more temporal and contextual serial order effects. Instead of including item-item connections (as in Chaining Theory), context was simulated by linking sets of items to different control nodes. Reactivation of multiple items could then be achieved by the activation of a single control node, with the learned size of these control nodes thus seen as grouping effects. Connections between control nodes and their items are then periodically (i.e. temporally) 'refreshed,' which accounts for grouping effects due to presentation rate.

Errors result from perturbations in the order of items during reactivation, and increase as a function of the density of items stored within an arbitrary time interval, thereby reducing the distinctiveness of the portion of a signal associated with a particular item. This allows items in close spatial-temporal proximity to be highly confusable, thus replicating a robust finding in the experimental literature.

The notion of distinctiveness has also been incorporated by other models of serial-order memory, based on both global (Murdock, 1960) and local properties of a sequence (Neath, Brown, McCormack, Chater, & Freeman, 2006). More recently, models have been developed that use dynamic learning-context signals that use a competitive process of activation and inhibition to determine which item is retrieved from memory (for a review, see Brown et al., 2000). One such model proposed by Brown et al. (2000) assumes that the synchronicity of such a dynamic learning-context signal with incoming evidence provides an elegant means to model serial-order memory in a neurologically plausible fashion (for a discussion of concerns with this model see Lewandowsky et al., 2006).

In more concrete terms, Brown et al. (2000) have likened the model to a clock. As the hour and minute hands move over the face of the clock, an item is associated with a particular time. To retrieve an item, one need only turn back the clock to the starting point and allow the clock to run its course.

For the present study, we adopted the Brown et al. (2000) model of OSCillator-based Associative Recall (OSCAR) due to the neurological plausibility and its ability to retrieve items in memory by simply reinitiating the learning-context signal. However, we readily acknowledge that other models may be capable of modeling the present data (e.g., Henson, 1998). Given that we are not directly concerned with a comparative analysis of short-term memory models, but rather seek to identify the mechanisms underlying the category-order effect, we do not address these considerations here.

### **OSCillator-based Associative Recall**

OSCAR assumes a set of endogenous oscillators, each represented as a sinusoid of a different frequency that varies over time. Together, these oscillators create a dynamic

learning-context signal, a portion of which is associated with each item that is presented to the model using a one-shot Hebbian learning rule. Once an item is stored, serial-order recall simply requires resetting the learning-context signal to its initial state whereupon each item is retrieved in the order in which it was presented.

Three features of the dynamic learning-context signal are critical to the model as implemented in the present study (for a more in-depth discussion, see Brown et al., 2000). First, the similarity of the components of an oscillation pattern determines the distinctiveness of the learning-context signal. In a non-repeating signal, when two states are proximal to one another they will have greater similarity than those that are distal. This leads to a second property: the learning-context signal is capable of creating a distinct representation for the relative order of items in a sequence. In order to accomplish this, an oscillation pattern must not repeat over a given interval of time. This is akin to winding back the arms of an analog clock and letting it run through again.

Another feature of the learning-context is that it can store hierarchical representations: information from different groups of items can be encoded using the same context signal. Confusability between portions of the learning-context signal (i.e. transposition errors) can occur when items occupy the same position in different sequences.

### **Modified Oscillator model: OSCAR-COE**

Our model of oscillator-based recall assumes three critical factors for the determination of the category-order effect. First, as was observed by earlier studies, the category-order effect is dependent on the rate of stimulus presentation (Greene & Lasek, 1994). This is instantiated in our model by assuming that rapid presentation of stimuli reduces the learning rate thereby increasing the difficulty of accurately associating portions of the learning-context signal with an item for storage.

Second, in the original OSCAR model the density of the temporal neighbourhood of an item determined the distinctiveness of the learning-context signal. The more items in a temporal neighbourhood, the greater the confusability between items and the greater the resulting recall decrement. The category-order effect is assumed to result from the difference *between* the properties of items from different categories. We assume that the portion of the learning-context signal associated with an item becomes more distinctive as a result of prior associations stored in long-term memory. This would create something akin to an attentional template (Duncan & Humphreys, 1989) that guides the processing of the items during the encoding phase. In the present model two separate distinctiveness values are used during every trial to simulate the facilitation afforded by these existing memory traces. One of these distinctiveness values is assigned to the first set of four items presented whereas the other is assigned to the second set of four items.

Third, as in the simulations conducted by Brown et al. (Simulations 8 and 9; 2000), we modelled grouping effects by advancing the step of the learning-context signal for the first item in the second half of the memory item list. This allows for greater differentiation of the learning-context signal for those items in the first and second portions of the signal, respectively. However, since the learning-context signal has some degree of similarity within the portions of the memory items these items should be more confusable.

## Present Research

The present study models the experiments of Brooks & Watkins (1990) and Schoenherr and Thomson (2008) that examined the category-order effect. An important difference observed between these two studies is that whereas Brooks & Watkins reported greater recall for lists of single digits that preceded lists of words, Schoenherr and Thomson found that by equating the number of digits and words in a display, word stimuli became the more salient category.

### Simulation 1: Brooks and Watkins (1990)

Simulation 1 models the basic findings observed by Brooks and Watkins (Experiment 1, 1990; see also Young and Supa, 1941): that recall is improved when a more salient category precedes a less salient category. In order to achieve this, we assume that numeric digits are more distinctive than word stimuli due to limitation in the number of items that can be held in the focus of attention.

Although in general the lexical and phonotactic properties of words should make them more distinctive, the conditions used by Brooks & Watkins (1990) favour numeric digits. Words, both spoken and written, occur with far greater frequency than numerals. However, for the memory list examined here we assume that the words are unrelated and therefore there is no relational knowledge that facilitates encoding of the stimuli as a category. Elsewhere in the categorization literature, Murphy and colleagues (for a review see Murphy, 2000) have demonstrated that when relational knowledge is available it greatly facilitates stimulus encoding. However, if this knowledge is only general in nature it does not have any effect (e.g., Murphy & Allopenna, 1994). Indeed, although words can be related together if they are not from the same category they function merely as a subset of all possible words. Given that a lexicon of average college students ranges between 12,000 - 17,000 word families (e.g., Zechmeister et al., 1995) this makes the retrieval of any word potentially difficult if the set of all possible retrieval candidate cannot be narrowed.

For the purposes of Simulation 1, we assume that there is greater output interference with words than with numeric digits. This interference arises from the retrieval mechanism that underlies recall for numerals and letters. For the memory stimuli from the number category, Brooks and Watkins used only single digit numeric stimuli whereas they used numerous words that varied in length (e.g., cow, area, nickel, diamond). Thus, when a participant attempts to retrieve a number there are only 9 possible candidates (the

digit 7 was excluded as a memory item by Brooks and Watkins). By contrast when recall of unrelated words are attempted, lexical or phonotactic properties limit the subset of 26 possible letters for each position only marginally given that the word stimuli used in the experiment vary considerably in length.

## Method

The version of OSCAR used in the present study was programmed into MATLAB and modified from that used by Brown et al. (2000) in terms of the parameters mentioned below. This simulation modelled the results for 30 participants, each performing 160 recall trials. The number of trials was selected to make the findings commensurable with Schoenherr & Thomson's (2008) study. These trials were divided into two in terms of whether numbers or letters were assumed to constitute the first tetragram.

Distinctiveness was varied across category type. Numerals were assigned a higher distinctiveness value ( $D = 4$ ) relative to words ( $D = 3$ ). Again, the assignment of these values resulted from the associations assumed to exist in long-term memory (for the word stimuli) as well as the relative simplicity of the number stimuli relative to the unrelated words.

Grouping effects were obtained by moving the learning-context signal for the fifth item (this item marked the boundary between the first and second category) ahead at a much greater rate (*Step Size* = 4) than for all other items (*Step Size* = 3). Learning rate was adjusted to a one-shot Hebbian rule, representing a moderate presentation rate ( $LR = 1.0$ ). Output interference for words was accomplished by adding noise to the retrieval process. This same noise value was not included for numerals, assuming that participants need only recall a single item.

A caveat is also required. Although typically recall order effects are modelled in studies of memory, we make no attempt to do so here. Firstly, the OSCAR model was not designed to examine this procedure (although for suggestions see Brown et al., 1990), and second, other studies examining the category-order effect have observed no significant effect of recall order (Greene & Lasek, 1994; although for some suggestive findings see Schoenherr & Thomson, 2008). We therefore bypass this consideration in developing the OSCAR-COE model.

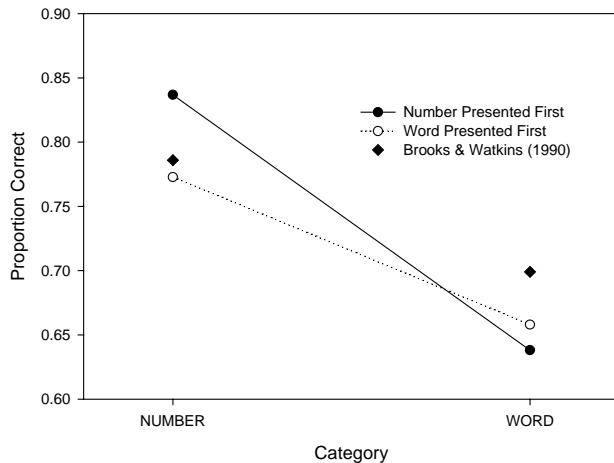
## Results

The results are presented in Figure 1. As is immediately apparent, a similar pattern of results is observed as those found by Brooks and Watkins (1990). When the number category precedes the word category, OSCAR-COE recalled a greater number of items than when words preceded numbers.

## Discussion

It should first be noted that Brooks & Watkins (1990) used the number of items recalled as their dependent measure whereas our analyses used proportion correct. Additionally,

their analysis collapsed item recall over both numerals and words whereas our analysis separated the two. However, a similar pattern to their observation that digit-word recall (7.07 items) was greater than word-digit recall (6.29 items) is evidenced in the means response of the model presented above. OSCAR-COE responses were in fact more dramatic than Brooks & Watkins (1990) findings, but can be achieved by allowing for further adjustments in the distinctiveness of the learning-context signal for both numeric and word items.



Although Simulation 1 models only one experiment of Brooks and Watkins (1990) study, it can be readily extended to other experiments conducted within that study as well as other studies (Greene & Lasek, 1994; Young & Supa, 1941).

These findings suggest that the category-order effect results from the grouping of items in memory. Early versions of the OSCAR-COE model simply advanced the learning-context signal as a single chunk of memory items, which did not produce differential recall patterns for the various categories. Thus, the further iteration of the learning-context signal was required to instantiate a category-order effect. Simulation 1 demonstrates that the number of associations in long-term memory should interact with presentation order and output interference from retrieval in order to produce the category-order effect.

The use of greater distinctiveness values for the numeric stimuli stems from the number of prior associations in memory as well as the limits of the number of items that can be held in the focus of attention during encoding. However, as noted by Schoenherr and Thomson (2008), this comparison is unbalanced in that if we consider the number of elements in each memory item that need to be retrieved, there are far greater demands for encoding word stimuli in the absence of any association between them.

Simulation 2 sought to align the findings of early experiments that have observed the category-order effect with those found by Schoenherr and Thomson (2008). For

the purposes of Simulation 2 by modelling a situation in which equal numbers of stimuli were used in both categories of tetragrams.

## Simulation 2: Schoenherr & Thomson (2008)

Simulation 2 sought to replicate the findings of Schoenherr & Thomson (2008). Schoenherr and Thomson (2008) used four tetragram categories: words, pseudo-words, rhyming letters (i.e. b, c, d, e, g, p, and v), and random letters. One letter tetragram was paired with one random number tetragram creating compound stimuli that was presented for a brief duration (750ms in Experiment 1). Recall performance was observed to improve when words and pseudo-words were presented first as well as when random numbers preceded rhyming and rhyming letters. These results not only confirmed the category-order effect but indicated that it can be observed at rapid presentation rates. The findings that numeric stimuli enjoyed only a relative advantage in comparison to letter stimuli provided evidence for the prior associations in memory are also determinants of the category-order effect.

As noted above, in Experiment 1 of Schoenherr and Thomson (2008), a category-order effect was observed wherein word and pseudo-word items were more accurately recalled than numeric stimuli. Sequences of random and rhyming letters were recalled with less accuracy than numeric stimuli. In order to draw a parallel with Brooks and Watkins (1990) we assume that the various lexical and phonotactic properties of words stored in long-term memory facilitate encoding of stimuli in comparison to four digit memory items that have no prior associations (i.e., they do not represent a historic date or any other meaning number sequence such as pi). Thus, while the same number of items are in the focus of attention for both categories the number of associations those items have in memory differs. As a result, an attentional template (Duncan & Humphreys, 1989) is capable of guiding processing more efficiently for those items with a greater number of associations.

## Method

The model was modified from Simulation 1 but used the same parameters for the number of participants and trials. Each category is associated with a separate distinctiveness value, and are further assumed to change with the number of associations in long-term memory that facilitate allocation of attentional resources.

Word stimuli are assumed to be the most distinct having both lexical and phonotactic properties ( $D = 4$ ). Pseudo-words were assumed to contain fewer word-like properties (e.g. evincing only phonotactic structure), and were consequently less distinctive than words ( $D = 3.5$ ). Numbers were assumed to be drawn from a small set that while not having complex associations are nevertheless memorable due to their small set size in memory ( $D = 3$ ). Finally, given that random letters and rhyming letters are drawn from the set of all letters stored in memory, we assume equivalent values that are relative indistinct ( $D = 2$ ).

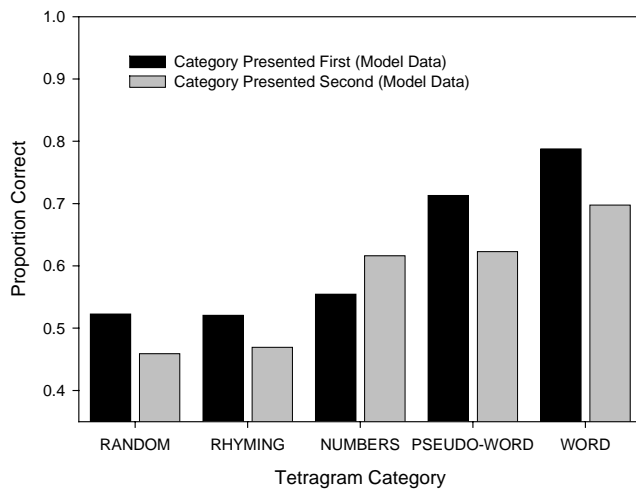


Figure 2A. Modelled data for Schoenherr and Thomson (2008): Category-Order Effect over Tetragram Category

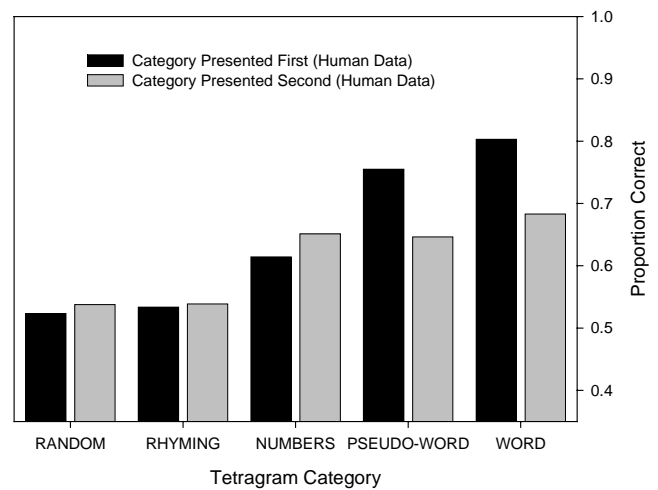


Figure 2B. Human data for Schoenherr and Thomson (2008): Category-Order Effect over Tetragram Category

Given that an equivalent number of memory stimuli were presented from each category (i.e., 4 letters or numbers) we assumed that there was no differential output interference and so did not include it in the model. Grouping effects were modelled in the same fashion as Simulation 1. The learning rate was reduced from the one-shot Hebbian ( $LR = 0.8$ ) to model a more rapid presentation relative to Simulation 1.

## Results

As in Simulation 1, OSCAR-COE was capable of generating the category-order effect. As is clear from Figure 2A, the means show a comparable pattern of performance to those reported by Schoenherr and Thomson (2008; reproduced in Figure 2B). When words or pseudo-words preceded numbers they are more accurately recalled than when they follow numbers. It is also clear that numeric stimuli were more salient than rhyming or random letters. The Spearman's rank correlation coefficient for the means of these two data sets revealed that this trend was highly significant,  $r = .879, p < .001$ .

## Discussion

As in Simulation 1, differences in the distinctiveness of the learning-context signal again proved to be a critical feature when modelling the category-order effect. When the more salient categories were presented first, they facilitated overall encoding of stimuli by focusing attention on attributes of the memory items. By allowing for the grouping of items recall performance improved between the tetragram.

It should be noted that there are difference in performance for the number, random letter and rhyming letter conditions than were observed by Schoenherr and Thomson (2008). Namely, Figure 2 demonstrates that when random and rhyming letters precede numeric stimuli recall was improved relative to when they followed numerals. This same pattern was observed for numbers. However,

Schoenherr and Thomson (2008) found roughly equivalent recall patterns regardless of the presentation order. This shortcoming is not critical though as it could have conceivably resulted from greater output interference for those items presented second or simply a failure to account for recall order (see above). In either case, OSCAR-COE accounts for the major empirical trends.

## General Discussion

The overall findings of this paper suggest that OSCAR-COE can effectively model the category-order effect by varying the distinctiveness of the learning-context signal, allowing for item grouping, and by varying the learning rate. This suggests a central role for the prior associations of items stored in long-term memory.

The present study also has ramifications for models of memory. Although it has elsewhere been argued that classical models of memory are incapable of replicating certain errors during retrieval (Brown et al., 2000; Henson, 1998), it is also clear from OSCAR-COE that a means is required to account for facilitation of encoding of items in memory. Without some ability to model associations stored in long-term memory, any neural architecture may fail to account for performance patterns that can only arise out of these associations. Even the present model cannot fully duplicate the effects of long-term memory as we modeled it here indirectly through assumptions regarding distinctiveness.

Given the complex nature of the category-order effect, further studies need to be performed to bridge the gap that exists in the experimental literature. The present study demonstrates that when differences in distinctiveness of the learning-context signal are accounted for the category-order effect is produced.

However, distinctiveness has been modelled here as a unidimensional construct. Instead it seems more than likely the difference between implicit knowledge of prior association and explicit relational/theoretical knowledge

retained in memory should be considered. It is likely that the variety of stimuli used thus far (for reviews see Greene & Lasek, 1994) produce the category-order effect for different reasons. That the effect can be caused by separate sources of knowledge suggests that one source (e.g., implicit knowledge) may be more robust than another source (e.g., explicit knowledge; for a consideration of this sort see Reber, 1992). If so, different modes of interference should be capable of disrupting encoding of these various kinds of associations.

Similarly, further investigations must be performed to determine how attention facilitates the encoding of information in the context of the category-order effect. Although the work of Schoenherr and Thomson (2008) and the presented study suggest that the primary influence of attention is at the perceptual level during the encoding phase of memorization this has yet to undergo empirical investigation. Although Greene & Lasek (1994) used articulatory suppression, tasks that target executive functions could disrupt encoding of higher-order relations.

OSCAR-COE also provides predictions for future studies. If the distinctiveness is a function of the number of associations in memory that creates a processing template to facilitate encoding of items, than increases in the quantity of numeric items should result in a concomitant decrease in the category-order effect for numeric stimuli.

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