

Neuromuscular Control Contributes to Incidental Learning
Head Orientation During Visual Statistical Learning

by

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ABSTRACT

Incidental learning of sequential information occurs in visual, auditory and tactile domains. It occurs throughout our lifetime and even in nonhuman species. It is likely to be one of the most important foundations for the development of normal learning. To date, there is no agreement as to how incidental learning occurs. The goal of the present set of experiments is to determine if visual sequential information is learned in terms of abstract rules or stimulus-specific details. Two experiments test the extent to which interaction with the stimuli can influence the information that is encoded by the learner. The results of both experiments support the claim that stimulus and domain specific details directly shape what is learned, through a process of tuning the neuromuscular systems involved in the interaction between the learner and the materials

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INTRODUCTION

People isolate and learn regularities in novel, complex environments. We use dynamic visual patterns to aid visual search (Chun, 2000). We use stochastically determined patterns of visual stimuli to reduce reaction time when learning to produce specific button presses in series (Cleeremans & McClelland, 1991). Even as pre-verbal infants, there is evidence that we utilize information about the probability of specific syllable-to-syllable transitions in speech to segment a streaming auditory signal into discrete words of our native language (Pelucchi, Hay & Saffran, 2009). What is common to all of these instances is the process of incidental pattern learning. That is, the automatic acquisition of knowledge, without awareness or intent, that aids in the subsequent processing of sequential information.

The goal of my research is to understand the nature of the information that is encoded during the incidental learning of visual sequences. Two opposing accounts exist in the current literature. One account posits that learners extract the structural rules underlying the sequences, whereas the alternative account posits that the implicit imitation of the stimuli leads to neuromuscular tuning. The following will describe the paradigm that is commonly used to study incidental learning. Then two experiments will be reported, which lend support to the neuromuscular tuning account of incidental learning.

Incidental pattern learning has been studied in a number of disciplines. In the cognitive literature, the paradigm is called artificial grammar learning (AGL), and it is often studied in the context of implicit learning, memory or attention

(Pothos, 2007). In the developmental literature, it is called statistical learning (SL), and it is often studied more strictly in the context of implicit learning (e.g. language-acquisition). The term SL is also present in the broader cognitive literature, especially with reference to visual statistical learning (VSL). The common focus for all methods of study is that unintentionally tracking the relations among successive stimuli produces more skillful interactions over time. For the purposes of this paper, AGL is treated as a synonym for SL (cf. Perruchet & Pacton, 2006), since the similarities between the literatures far outweigh any minor differences in methodology. Thus, the focus of the present paper will be on the possibility of a common process that contributes to incidental pattern learning in general.

To understand the study of probability-based incidental pattern learning (just “incidental pattern learning” from now on), one must understand the creation of the stimuli. A small set of stimulus items, usually ranging from 5 to 10 distinct items (e.g. a set of five numbers), are arranged by a finite state grammar (c.f. Reber, 1967). Because stimulus items are presented in sequence, the finite state grammar is simply a set of artificial “rules” that describe when each stimulus item can occur within a sequence (see Figure 1).

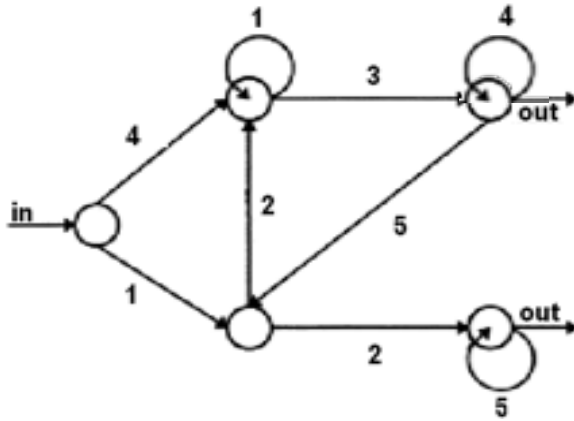


Figure 1. Finite state grammar used to construct the sequences for Experiments 1 and 2. Grammatical sequences must start at the “in” gate, follow the direction of the arrows, and end at an “out” gate. All sequences that were used ranged from 3 to 6 total items in length.

Each sequence is from 3 to 8 items in length in an average experiment. There can be both grammatical (G) and nongrammatical (NG) sequences. G sequences follow all of the rules of stimulus to stimulus transition, whereas NG sequences break at least one of the rules. Note that the grammar strictly dictates the sequential ordering of the stimulus items within each G sequence. For example, a finite state grammar usually contains a very limited set of beginning and ending stimulus items, as in Figure 1. This means that all G sequences will begin with one of the limited set of legal items (e.g. 1 or 4) and end with one of the limited set of legal items (e.g. 3 or 5). The sequential constraints are defined by the set of legal transitions between individual stimulus items, which is tied to that items place within each fixed-length sequence. Looking at Figure 1, a “1” at

the beginning of a sequence will always be followed by a “2,” while a “1” in the middle of a sequence might be followed by another “1” or a “3”.

The typical incidental pattern learning experiment is conducted in two phases. Participants are first exposed to a large subset of the G sequences. This is often referred to as the learning phase. Participants are not made aware of the finite state grammar during the learning phase; they are usually told that they are completing some sort of memory task. Following the learning phase, participants are informed of the fact that there were rules that controlled how the sequences were constructed. The second phase of the experiment is called the testing phase. During the testing phase, participants are exposed to the novel subset of G sequences (e.g. the G sequences not included in the learning phase) along with an equal number of NG sequences. Participants are asked to discriminate between G and NG sequences. Learning is indicated by the ability to perform this discrimination at above chance accuracy.

There is still no consensus on the nature of the mechanism(s) that drives incidental pattern learning. Traditionally, it was assumed that people abstract the underlying rules of the finite state grammar (e.g. Reber, 1967). This is known as the rule-based approach. However, contemporary explanations favor connectionist models that use back-propagation to incorporate temporal (sequential) information and thereby produce similar patterns of anticipatory learning as observed in the AGL literature (e.g. Cleeremans & McClelland, 1991; Dienes, 1992; Stadler, 1992; Kinder & Lotz, 2009). The connectionist framework is known in this literature as the similarity-based approach. But even if the field

could agree on some similarity-based model, the question still remains as to the nature information that is encoded during learning. What information should we feed into the model? How specific is it? How modal? How abstract?

On this topic, there are two contrasting schools of thought. The domain-general approach proposes a single higher-order learning mechanism that is capable of abstracting the statistical relationships between successive stimuli regardless of the nature of those stimuli (e.g. Kirkham, Slemmer & Johnson, 2002). This theory is based primarily on the fact that incidental pattern learning occurs in multiple domains (especially studied in both visual and auditory domains) and from a very early age. Additionally, there is some evidence that transfer of incidental pattern learning can occur from one stimulus set to another (across arbitrarily related domains and/or symbol sets)(Tunney & Altmann, 2001). In contrast, the domain-specific approach proposes any number of low-level learning mechanisms that are driven more directly by the nature of the stimulus items themselves (e.g. Conway & Christiansen, 2006; Witt & Vinter, 2012). This approach is rooted in evidence that stimulus-specific details constrain incidental pattern learning in such a way that people can learn multiple grammars at once, provided that the stimuli comprising each finite state grammar are sufficiently perceptually distinct (i.e. they must systematically vary from one another along an easily identified feature like size, shape or color). Additionally, there is evidence that different modalities display unique capabilities in terms of the rate and retention of information that is learned during an incidental learning task (Conway & Christiansen, 2005). Finally, the evidence in strong support of

transfer has been called into serious question (c.f. Reddington & Chater, 1996). Though it may seem at first that the domain-general approach ought to favor the rule-based model of acquisition mentioned before whereas the domain specific account should have a special claim on similarity-based models, this is not necessarily the case. In fact, a domain-free account might easily be instantiated in a connectionist model (i.e. higher-order, abstract symbols might be fed into such a model and still produce a similarity-based decision process). To reiterate, the crucial question is in regard to the nature of the information (higher-order symbolic or perceptually-driven domain-specific) that is encoded during the learning phase.

The present experiments support the domain-specific account of incidental pattern learning. It is argued that the apparent domain-general nature of incidental pattern learning is at least partially due to a common feature to all perception-action systems: neuromuscular tuning.

NEUROMUSCULAR TUNING

The neuromuscular tuning (NMT) hypothesis is derived from evidence of embodied, implicit imitation of environmental stimuli (Barsalou, 2008; Topolinski & Strack, 2009; Yang, Gallo & Beilock, 2009). Different neuromuscular systems (e.g., eye-movement control, speech articulators) are operational in different incidental pattern learning tasks. As each stimulus item is presented in a sequence, a particular neuromuscular system responds by tracking and/or imitating the stimulus. As the next stimulus item is presented, the system must transition to a new state. Because incidental pattern learning tasks will present G stimulus transitions repeatedly, the system engaged in implicit imitation is tuned to make those transitions. After sufficient exposure, G sequences can be tracked with greater fluency than NG sequences (for which the transitions have not been tuned), allowing for discrimination between the types of sequences during the testing phase. If the NMT account is accurate, then learning will be domain-specific insofar as the transitions between stimuli can be tuned within a single, low-level perception-action system (e.g. eye-movement control versus speech-articulators).

In contrast to the similarity-based, NMT account of incidental learning, the domain-general approach to incidental learning holds that the specifics of the stimulus item are secondary to the abstract representation that results from perception. Thus, there can be either a strong or a weak version of the domain-general approach. The strong version posits that low-level features are inconsequential to incidental learning (favoring the classic, rule-learning model of

incidental learning), while the weak version would posit that low-level perception-action systems might act as a gate or filter to the information that is abstracted. The weak version of domain-general learning could potentially fit with a similarity-based model. Importantly, however, the domain-general approach must predict that low-level features of the stimuli will not be present in the resulting representation of the grammatical structure.

Our previous work (Marsh & Glenberg, 2010) addressed both the strong and the weak versions of the domain-general account. Using bimodal stimuli (each auditory stimulus was presented simultaneously with a paired visual stimulus), we demonstrated that incidental learning of transitional probabilities readily occurs within a modality (i.e. auditory component to subsequent auditory component) but not between modalities (i.e. auditory component to subsequent visual component). Thus, there was no support for the strong domain-general account.

Marsh and Glenberg's (2010) second experiment (using the same stimuli) addressed the weak account, which might hold that the perception-action filter would prevent an alternating (auditory to visual) representation from forming, while the resulting representation should still be free of perception-action level encoding. The NMT account, in comparison, predicted that the laryngeal system would be selectively involved in both the acquisition and expression of incidental learning for the auditory component. Supporting the NMT account, a secondary auditory task involving the larynx during the testing phase (i.e. humming, contrasted with syllable production or stomping feet) selectively disrupted

performance the auditory transitional probabilities. Visual learning was not affected by any secondary task. Thus, the NMT hypothesis does a better job of accounting for our previous work. Here we expand this finding by demonstrating that neuromuscular tuning of the eye-movements plays a role in the incidental pattern learning of spatiotemporally distributed visual patterns (Fiser & Aslin, 2002; Fiser & Aslin, 2005), which is separable from the NMT that occurs in the auditory modality.

The following experiments will assess whether or not the physical orientation of the learner to the visual materials (i.e. the angle from the person's head to the computer screen) is encoded during incidental pattern learning. Participants will receive both auditory and visual information. The participants' relative orientation to the material will be manipulated (Same or Different from learning to test phase). If incidental pattern learning is based on a domain-general process that tracks conditional probabilities, then the learners orientation to the material should have little affect other than, perhaps, disrupting performance equally for the visual and auditory test sequences due to unusual posture or changes in posture. In contrast, if incidental pattern learning reflects neuromuscular tuning, grammaticality judgments should reflect an interaction of Same or Different head orientation and the Modality (auditory or visual) of the stimuli. The Different orientation should reduce discrimination in the visual modality (because eye movements used to track visual stimuli during the test are different from those tuned in learning) more than in the auditory modality.

EXPERIMENT 1

Materials

A finite state grammar (adopted from Gomez & Gerken, 1999; see Figure 1) was used to generate 36 G sequences. Sequences were expressed simultaneously in visual and auditory modalities. In the visual modality, a small, black box occurred at one of five locations on the computer screen (the center of the monitor or one of the four corners). Each box location was accompanied by one of five tones (210, 245, 288, 333, and 385 Hz) so that the box locations and tones were completely redundant with one another. Items within a sequence were presented for 250 ms with a 150 ms blank and silent interval between each (see Figure 2).

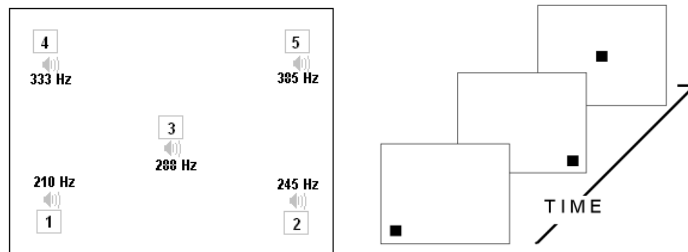


Figure 2. Left: The large rectangle represents the layout of the computer screen for Experiments 1 and 2. The five numbered boxes show the five possible locations of the visual stimuli and beside them are the five possible tones (in Hz) associated with each location. **Right:** A graphical representation of the visual sequence “1 2 3” as it would have appeared.

Of the 36 G sequences generated, 24 were used during the learning phase and 12 were used during the testing phase (along with 12 NG sequences, created by violating one of the sequential rules of the grammar; see Appendix A for a complete list of the sequences used). Orthogonally, half of the sequences in the test phase were presented in the visual (V) modality (blocked) and half in the auditory (A) modality. The order of block (V or A) and specific test sequences that comprised each block was counterbalanced.

Procedure

During the learning phase, G sequences were presented in pairs. After every pair, the participant responded whether the sequences in the pair were identical (50% of the time) or not. Participants were randomly assigned to one of two head rotation conditions: Rotated (45 degrees to the left) or Straight (directly facing the screen). Head rotation was maintained using a chin-rest (see Figure 3). Note that in the Rotated condition, eye movements used to track the visual stimuli are distinctly different from those used in the Straight condition. However, laryngeal imitation of the tones should be largely unaffected by head rotation.

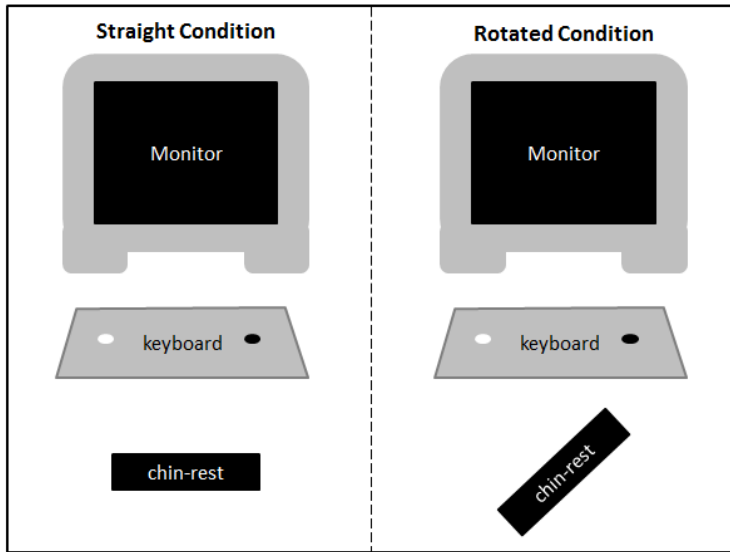


Figure 3. Experimental setup for Experiment 1. The “Same” key is shown in white. Participants completed the learning phase either in the Straight (**left**) or Rotated (**right**) Condition. During the test phase, participants either maintained the same orientation or the chin-rest was moved to the different condition.

Participants were informed, before the test phase, that there were underlying rules, but the details of the rules were not specified (See Appendix B for the script that RAs read to the participants). During test, participants judged if each novel sequence was grammatical or not. Participants were randomly assigned to one of two head orientations: Same or Different compared to head orientation in the learning phase.

Results

We analyzed data from the 72 participants who performed in the top 75% during the learning phase (19 were excluded). In the learning phase, participants'

only task was to determine if two sequences were the same as one another, so removing the lower 25% of scores on the learning phase task from the analyses assures that people who did not attend (and therefore did not learn) do not skew the results. This particular criteria was chosen after examining the data from both experiments, and it was found that removing the bottom 25% of learners eliminated all of the outliers in both cases.

In an analysis of learning phase accuracy, there were no significant effects (all $ps > .3$). Data from the test phase were analyzed using learning phase accuracy as a covariate. There was no significant main effect of the starting orientation (i.e. straight vs. rotated during the learning phase; $p = .151$), nor was there a three way interaction ($p > .8$). There was, however, a significant Modality by Same/Different interaction ($F(1, 67) = 4.17, p = .045$; see Table 1 for the complete set of means). When tested solely in the auditory modality, participants were slightly more accurate in the Different condition; whereas when tested solely in the visual modality, as predicted, participants were less accurate in the Different condition than the Same condition. Analyzing the auditory sequences alone produced no significant effects (all $ps > .3$). Analyzing the visual sequences alone did produce a significant effect of starting orientation. Participants who were trained in the Rotated condition ($M = 9.48, SE = .27$) performed better than those trained in the Straight condition ($M = 8.76, SE = .27; F(1, 67) = 4.35, p = .041$), even though there was no significant difference in learning accuracy between these groups ($p > .9$). Interestingly, Same ($M = 9.41, SE = .27$) versus

Different ($M = 8.76$, $SE = .27$) orientation from learning to test was only nearly significant ($p = .09$).

Table 1

Complete list of Means, Experiment 1

Learning	Testing	Visual Sequences	Auditory Sequences
Rotated	Same	9.91 (.36)	9.35 (.38)
	Different	9.05 (.39)	9.42 (.42)
Straight	Same	8.90 (.39)	8.97 (.42)
	Different	8.47 (.38)	9.69 (.41)

Note: Number of correct discriminations (out of 12) adjusted for performance during the learning phase (standard errors in parentheses)

Discussion

The pattern of the data are difficult to reconcile with an domain-general account of incidental pattern learning based solely on representing abstract conditional probabilities since the abstract rules did not change regardless of the orientation of the headrest. Changing the orientation of the headrest selectively changed the eye movements that would be required to track the visual stimuli. The NMT prediction is supported: In the overall analysis, changing the head rotation disrupted grammaticality judgments for the visual sequences when compared to auditory sequences. When the ocular-motor tuning is disrupted (Different condition), so is discrimination performance for the visual test

sequences compared to the auditory test sequences. Importantly, the same head turning manipulations made no significant difference in performance on the auditory sequences for which tuning in the laryngeal system is important (Marsh & Glenberg, 2010).

However, there was a caveat to the results that bear mentioning. In a direct comparison between subjects of the visual sequences alone shows that there was a main effect of starting orientation. Thus, people who viewed the learning sequences in their periphery were doing better on the test sequences, regardless of whether they maintained the same orientation. Better test performance when trained in the Rotated condition is not too surprising, given that rods (primarily concentrated outside the foveal region of the retina) are more responsive to movement, and the visual stimuli used in this study were defined by relative placement on the screen. Therefore, encoding of the visual sequences for participants not directly facing the screen was likely more robust. This presumed difference in encoding does present a problem for our analysis since it introduces more variance into the between subjects comparison. In order to minimize this difference and to concentrate more power directly on the comparison of Same versus Different orientation, a second experiment was conducted.

EXPERIMENT 2

There are four important motivations for Experiment 2. The first was to replicate the novel finding that visual test sequences are disrupted by changes in relative orientation. The second was to eliminate the added variance that the Rotated versus Straight learning conditions introduced. Third, we wanted to show some level of generalizability of these findings by using a different experimental setup. Finally, the experiment was designed to address concerns about the variability being introduced by having a bimodal stimulus item during learning (i.e. auditory and visual modalities) as compared to a unimodal stimulus (i.e. visual only). Whereas the first motivation is common practice, the other three will be explained in more detail.

Because we are interested in how changing relative orientation to a visual stimulus affects incidental learning, we needed to remove any added sources of variance. Given that participants did better in the Rotated condition in Experiment 1, we chose only to train people with stimuli presented peripherally. This should produce stronger learning overall and allow a majority of the between subjects variance to be accounted for by our between subjects manipulation of Same versus Different orientation from learning to test. Additionally, we were concerned with generalizability of our initial findings. Was it the case that people did worse on the visual sequences when they had to move their head because they had to move their head? Or was it just the relative orientation that mattered? In other words, could we replicate these findings by keeping the person's orientation constant while changing where in the environment the visual information was

located? To address both issues, we modified the experimental setup. In Experiment 2, we used two monitors located at a 45 degree angle on either side from the forward facing chin-rest. The Different condition was accomplished simply by changing the monitor that displayed the visual information. This set-up had the added effect of assuring that every participant in the Different condition received exactly the same relative changes in orientation since nothing needed to be physically moved (whereas in Experiment 1, the chin-rest needed to be adjusted each time and so potentially more variability was introduced.)

The final motivation stems from an important but separate issue. There are known differences in temporal pattern perception between auditory and visual information (Garner & Gottwald, 1968; Handel & Buffardi, 1968; Glenberg & Jona, 1991; Conway & Christiansen, 2005; Emberson, Conway & Christiansen, 2011). In short, it appears that faster frequencies of serial presentation (like the 250 ms presentation and 150 ms ISI used here) favor auditory pattern learning, while slower frequencies are better learned in the visual modality. Therefore, there is reason to think that participants might be more focused on the auditory component of the bimodal stimuli during the learning phase (given that it is easier to compare two auditory sequences at this rate of presentation). If that is the case, then encoding of the visual component of the learning sequences might be inherently variable. Some participants might neglect the visual component all together, whereas others might attend to both aspects of the bimodal stimuli. To test the impact of using bimodal learning sequences, we introduced a between-subjects condition. Some participants were trained with the same bimodal stimuli

as before, whereas others received only visual information during the learning phase. Comparing these groups will allow us to directly test the hypothesis that participants do worse on the visual test sequences (only) if auditory information is available during learning.

Participants in Experiment 2 only received visual test sequences, as we were confident in the noncontroversial finding that changing relative orientation has no effect on auditory sequences (heard through headphones). This difference in the test sequences allowed us to concentrate more power on the visual modality by using all 24 test sequences in the visual modality (whereas we had to split the available test sequences between the modalities in Experiment 1).

Materials

All stimuli were identical to those used in Experiment 1, with the exception that half of the participants were trained with only the visual component of the stimuli. At test, participants only received visual sequences regardless of their learning condition.

Procedure

As in Experiment 1, the learning phase consisted of pairs of G sequences, which participants judged as being either the same or different from one another. Participants' heads were always facing directly forward (held in place by a chin-rest). They were randomly assigned to one of two monitor conditions: Left

(information appears on a monitor 45 degrees to the left of the central chin-rest position) or Right (on a monitor 45 degrees to the right of center). The keyboard was centrally located, turned lengthwise between the two monitors, with the “same” key located nearer the participant and the “different” key further from where they were seated (see Figure 4). Similar to Experiment 1, eye movements in the Left monitor condition were distinctly different than those used to track the visual stimuli in the Right monitor condition.

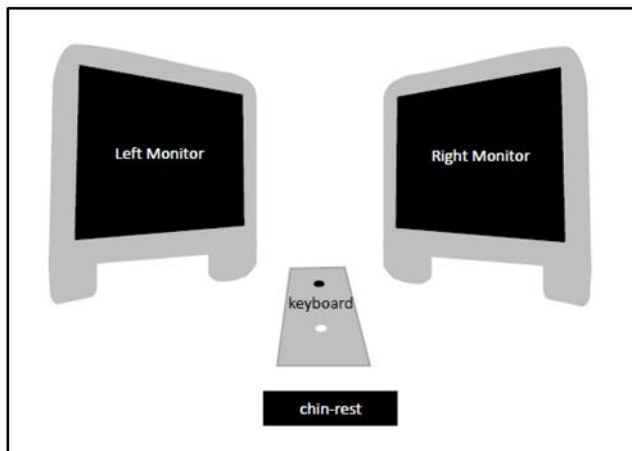


Figure 4. Experimental setup for Experiment 2. The “Same” key is shown in white. Participants completed the learning phase on either the Left or Right monitor. During the test phase, participants either used the same monitor or switched to the different monitor.

Participants were informed, before the test phase, that there were underlying rules, but the details of the rules were not specified (see Appendix C

for a complete script of the instructions that the participants heard/read).

Participants then judged if each novel visual sequence was grammatical or not. Participants were randomly assigned to one of two relative orientations: Same or Different compared to the monitor that was used during the learning phase. If the findings of Experiment 1 replicate, then grammaticality judgments should reflect a main effect of Same or Different orientation. This finding would provide more generalizable evidence that relative orientation of the observer to the stimuli is encoded during incidental learning of spatiotemporally distributed visual information and that the orientation contributes to performance. Additionally, if participants in the bimodal learning condition perform worse than those in the visual-only learning condition, it will warrant further investigation of the manner in which attention is distributed for bimodal (auditory and visual) stimuli during rapid serial presentation. If, however, there is no difference, then it will support the original NMT hypothesis that two distinct perception-action systems can be tuned relatively independently of one another.

Results

Using the same exclusion criteria as Experiment 1, we analyzed data from 74 participants who performed in the top 75% during the learning phase task (23 were excluded). It should be noted that the participants in the bimodal stimulus condition performed significantly better on the learning phase task than participants in the visual-only condition ($p < .01$). Therefore, we calculated the top

75% for the bimodal and unimodal conditions separately before recombining the two groups to create the overall group ($n = 74$) of included learners.

Data from the test phase were analyzed using learning phase accuracy as a covariate. There was no significant main effect of the monitor location during the learning phase (i.e. left vs. right monitor; $p = .160$) or of stimulus type (i.e. bimodal vs. visual-only; $p = .476$) on their accuracy during the test phase. Likewise, none of the interactions were significant (all $ps > .33$). The only significant finding was a main effect of relative orientation. Participants in the Same monitor condition ($M = 18.81$, $SE = .45$) were better at discriminating G from NG sequences when compared to participants in the Different monitor condition ($M = 16.98$, $SE = .51$; $F(1, 65) = 6.91$, $p = .011$; see Table 2 for the complete set of means).

Table 2

Complete List of Means, Experiment 2

Learning Monitor	Test Monitor	V-Only Training Condition	AV Training Condition
Left	Same	19.15 (.92)	18.78 (.93)
	Different	18.60 (.97)	16.98 (1.0)
Right	Same	18.85 (.91)	18.46 (.93)
	Different	16.04 (1.1)	16.29 (1.0)

Note: Number of correct discriminations (out of 24) adjusted for performance during the learning phase (standard errors in parentheses)

Discussion

Once again, we demonstrated an effect of low-level embodiment (NMT) on the high-level cognitive task of visual incidental pattern learning. The results of Experiment 2 bolster our first demonstration by showing both the replicability and increased generalizability of the NMT hypotheses as applied to spatiotemporally distributed visual information. These results also suggest that participants are capable of learning such visual information presented at a rapid pace, regardless of the presence of auditory information. However, as was mentioned, participants did perform significantly better on the learning phase task (discriminating between two sequences) with auditory information available. This might be interpreted as supporting prior work, showing that sequential auditory information is more easily processed at the speeds used in these experiments (e.g. Emberson et al., 2011). Nonetheless, better performance on the learning phase task for the bimodal stimulus group did not lead to better performance on the visual test sequences (even when learning phase accuracy is removed as a covariate, $p = .281$). Thus, it may be the case that the auditory and visual perception-action systems are functioning in a largely independent fashion (at least, for such unnatural stimuli). This is to say, these findings are consistent with the assertion that eye movements used to track visual transitions tune one perception-action system while another system, controlling the larynx, is tuned to the auditory transitions. Participants did better on the learning phase task when

auditory information was available, but were equally capable of discriminating G from NG visual test sequences.

GENERAL DISCUSSION

In this concluding section, the results of the two experiments will be reviewed. Then some of the weaknesses of the NMT theory will be directly addressed and some possible solutions proposed. Finally, the NMT hypothesis will be extended to suggest future research within the domain of learning impairments.

The focus of these experiments was testing the domain-general against the domain-specific account of incidental pattern learning. Taken together, these findings strongly favor the explanation that the encoded information is not filtered by perception-action systems, but that it retains aspects of the domain-specific interaction. If this were not the case, then altering the relative orientation of the participant from training to test should not have selectively impacted test performance for the visual sequences.

Similarity-based approaches to modeling incidental learning, like simple recurrent network (SRN) models, can replicate aspects of human performance such as sensitivity to the frequency of stimulus items, the novelty of stimulus-to-stimulus transitions, and the position of items within a sequence (Kinder & Lotz, 2009). Until now, however, little work has directly asked what type of information should be fed into the SRN. Most SRN models of incidental pattern learning have used visual or auditory stimuli that are represented by simple, discrete symbols (e.g. letters or numbers; c.f. Mirman, Graf Estes & Magnuson, 2010). But in the real world, people are exposed to highly complex environments that contain multimodal information. Our findings here and in Marsh & Glenberg (2010)

suggest that encoding happens, at least in part, at the level of NMT. Thus, future SRN models might be more applicable to human learning if the information were not coded with discrete, abstract symbols but with reference to the embodiment of the learner (e.g. relative orientation for spatial information, the engagement of the larynx for tonal information, the articulators for syllables, etc.). In other words, neural nets need “bodies” if they are to behave like people.

Another intriguing extension of the NMT approach is that it allows a more direct conceptual connection between the cognitive science research on incidental learning in an artificial grammar learning (AGL) task and the neuroscience research on incidental learning in a probabilistically determined serial reaction time (SRT) task. Traditionally a very distinct paradigm, SRT tasks are studied in the context of motor learning and anticipation (cf. Robertson, 2007). The probabilistic SRT task involves training a person to perform a series of button presses, where the serial order of the buttons is either decided by a finite state algorithm (similar to AGL) or by a random series of numbers (c.f. Cleeremans & McClelland, 1991). Over time, participants perform the probabilistically determined button presses (akin to G sequences in an AGL task) significantly faster than they perform the random sequences (akin to NG sequences). Adopting a more embodied approach to understanding AGL, it is reasonable to assume that both AGL and SRT tasks involve tuning perceptual-motor systems to track the relations among successive stimuli. Learning in both cases can be conceptualized as skill acquisition, as opposed to abstract representation on the one hand and motor anticipation on the other.

So far, I have only discussed the strengths of the NMT approach, but there are at least two concerns with the hypothesis as it stands: 1) Can NMT theory account for incidental learning of nonadjacent dependencies? 2) Why, if NMT is really driving incidental learning, does performance not drop to chance levels when we selectively interfere with the neuromuscular system responsible for tracking stimulus to stimulus transitions? I will address each of these questions only briefly, starting with the first (and perhaps easier) one.

Can NMT theory account for incidental learning of nonadjacent dependencies? The phrase “nonadjacent dependencies” refers to more complex rules of a finite state grammar, where, for example, a stimulus item that appears at position 3 in a sequence is determined by the item at position 1 and not the item that directly precedes it. If incidental learning is going to work as a model of language acquisition, then any theory would need to account for learning of nonadjacent dependencies because they are commonplace in language-use. For example, subject-verb agreement can be a type of nonadjacent dependency (e.g. “The *girl* with the ball *was* playing,” versus “The *girls* with the ball *were* playing.”) Prior work has provided a number of important clues as to how this phenomenon functions. Gomez (2002) demonstrated that the variability of the intervening stimulus item predicts how well nonadjacent dependencies will be learned. Whereas a purely random intervening stimulus item (e.g. stimulus 2 could be any item) will lead to better nonadjacent learning, the more predictive the intervening item (e.g. stimulus 2 could be one of three items) the less likely a person is to learn the nonadjacent relationships (even if stimulus 1 is more predictive of

stimulus 3 than stimulus 2). From an NMT perspective, it can be assumed that there is some threshold of stimulus-to-stimulus frequency required before fluency can develop. When the intervening stimulus item is highly unpredictable, fluency will not develop and so the saliency of the nonadjacent preceding item may become more pronounced. This insight could inform future expansions on the NMT hypothesis. For example, it may be the case that a certain degree of predictability is required for people to imitate sequential stimuli. Stimuli that fail to reach that degree of predictability may not be imitated (and so longer range relationships that are predictable may become fluent).

Additionally, nonadjacent dependencies are learned more readily when the first and third items are perceptually similar to one another, yet perceptually distinct from the intervening stimulus. For example, people more easily learn the nonadjacent dependencies of a verbal artificial grammar when the first and third items are both plosive syllables (e.g. “ki” and “ga”) if the intervening syllable is continuant (e.g. “lo”). Keeping the grammatical structure the same, changing the third item to another continuant will greatly reduce the likelihood that the nonadjacent relationship is learned (Onnis, Monaghan, Richmond & Chater, 2005.) The same perceptual similarity principle applies to non-phonological stimuli as well, including music, pure tones and even Macintosh OS noises (Gebhart, Newport & Aslin, 2009). The NMT hypothesis would interpret “perceptual similarity” as a similarity in the perceptual-motor systems used to implicitly imitate the stimuli. As such, when nonadjacent stimuli engage the same neuromuscular mechanisms it would appear that people learn to associate them.

Moreover, NMT theory would make the novel prediction that nonadjacent dependencies between two plosives that engage the tip of the tongue (/t/ and /d/) should be learned more quickly than nonadjacent dependencies between plosives that engage the tip and the body of the tongue (/t/ and /g/) or the tip of the tongue and the lips (/d/ and /p/).

Now the harder question: Why, if NMT is really driving incidental learning, does performance not drop to chance levels when we selectively interfere with the neuromuscular system responsible for tracking stimulus to stimulus transitions? This question is difficult to address because there are any number of potential answers. For now, I will present just one. Perhaps NMT is driving the low-level encoding that forms the base of incidental learning, while higher-level processing is scaffold to this embodied structure. For example, in both Experiments 1 and 2 participants may simply have been tracking the patterns of box locations when they were first exposed to the visual sequences. After prolonged exposure to such a simple grammar, NMT would produce fluency of eye movements. Given this fluency, combined with the fact that the learning phase task required conscious comparisons between sequence pairs, participants might have developed rough heuristics to aid their task. Highly fluent patterns of box locations could have been thought of as relative to one another, instead of just being perceived as relative to the observer's body. For instance, a box in the bottom corner might consistently anticipate another box on the bottom of the screen. This can be thought of as a spatially distributed form of chunking (Meulemans & Van der Linden, 1997), where certain parts of the screen were

learned to be highly related to one another. Chunking allows more complex information (i.e. the details of the finite state grammar) to be treated as fewer units (i.e. “bottom,” “side,” “diagonal,” etc.), thus making it easier to keep track of these units either consciously or pre-consciously (in the form of active receptor fields). In this way, changing the visual orientation of the observer would simply require that the person be able to identify a mirrored version of those spatial units more often than chance (note that in the present experiment the change in orientation would only alter spatial relationships along the horizontal axis, but not those along the vertical axis).

Whether one accepts that explanation or not, it must be concluded that the results of the present experiments do not reconcile with the domain-free approach to incidental learning. At the very least, NMT (or some other low-level process) is encoding stimulus-relevant information that is actively contributing to performance at test. So far NMT-based hypotheses have found support in both the auditory (Marsh & Glenberg, 2010) and visual domains. Adopting a research perspective that recognizes the specific contribution of low-level neuromuscular systems in incidental learning might elucidate other areas of cognition that have been linked to performance on implicit learning tasks.

For an example, consider the current state of research on Specific Language Impairment (SLI). In the past, SLI was characterized by deficits in normal linguistic development in the absence of any other overt cognitive and developmental issues. More recent accounts have argued that SLI is often comorbid with motor deficits (Hill, 2001). After reviewing the literature on SLI,

Ullman and Pierpont (2005) argued that children with SLI actually suffer from a general deficit in procedural learning, which they call the Procedural Deficit Hypothesis (PDH). They argue that many of the deficits common in children with SLI are due to abnormalities in brain structures involved with procedural learning, especially in Broca's area. The PDH approach implies that SLI is not specific to language, but more generally to learning and coordinating sequential motor acts. Though there is considerable support for this hypothesis, there are many alternative approaches. Some researchers argue for specific grammar impairments (e.g. van der Lely, 2005). Others argue that SLI is primarily due to difficulty processing phonological information (e.g. Joanisse & Seidenberg, 1998). It is generally agreed that there are likely multiple subtypes of SLI, but there is still no standard method for differentiating them from one another.

Closer exploration of the connection between SLI and incidental learning might suggest a more structured view of SLI, its subtypes, and its connection to other linguistic deficits such as developmental dyslexia. Links between SLI and incidental learning have already been made. For example, Evans, Saffran and Robe-Torres (2009) showed that children with SLI (in contrast to age-matched controls) performed at chance levels on a statistical learning task involving verbal stimuli as well as one involving tonal stimuli. After extended practice, the SLI children matched performance of the controls for the verbal stimuli, whereas extended exposure to the tonal stimuli did not increase performance above chance. Because NMT predicts that different perceptual-motor systems are involved in imitation of verbal and tonal stimuli (i.e. articulatory and laryngeal

control, respectively), these findings might indicate that the SLI children included in this study had distinctive deficits in these two subsystems. Moreover, it might be the case that the larger group of SLI children could have been subdivided by the individual performance on either the verbal or tonal statistical learning task.

Taking an individual differences approach, Hedenius et al. (2011) linked grammatical aptitude with long-term consolidation of learning on an SRT task in both typically developing and SLI children. They found that, although SLI children could perform the procedural learning task at normal levels during acquisition, after two days the subgroup of SLI children with grammatical difficulties showed no signs of consolidation (i.e. longer-term storage of the procedural learning) whereas the subgroup with phonological difficulties showed normal consolidation. A similar correlation between grammatical aptitude and consolidation held for the typically developing children. The NMT hypothesis predicts that the perceptual-motor system involved in the acquisition of fluency for an SRT task is centered on fine motor control of the fingers (i.e., should not be affected by perceptual-motor systems involved in phonological processing). Thus, it makes sense that SLI children could perform this task normally. However, long-term consolidation of this learning might involve a different subsystem. Future research could focus on the connection between grammatical aptitude and memory, helping to extend the NMT hypothesis.

Finally, developmental dyslexia (DD) is commonly comorbid with an SLI diagnosis, though it is assumed to represent a separate disorder (Catts, 2005). Similar to SLI children, one review study shows that a majority of DD children

(75%) have significant deficits in phonological processing, and at least some children (50%) also show general motor deficits (Ramus, Pidgeon & Frith, 2003). Pavlidou, Williams and Kelly (2009) report that children with developmental dyslexia also show deficits in implicit learning on an AGL task involving shape stimuli, whereas typically developing children showed above chance learning on the same task. From a NMT perspective, this finding might support the hypothesis that incidental learning of visual stimuli (e.g. shapes) involves some form of verbal labeling (i.e. the poor performance of DD children results from difficulty with phonological processing). At least one study on children with DD claims that they do not show signs of deficit in an SRT task (Roodenrys & Dunn, 2008). Perhaps this is because DD children have a specific deficit in phonological processing, while fine-motor control is unaffected. Further analyses should test consolidation in DD children, since it is possible that they will show a distinct profile when compared with grammatically impaired SLI children. Moreover, further analyses of incidental learning tasks that specifically target the involvement of articulation and/or laryngeal control might show that DD is more likely to be comorbid in the subset of SLI children with phonological impairments (but not those with grammatical issues). Such a finding could begin to define two distinct etiologies for phonological and grammatical SLI subtypes.

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APPENDIX A

COMPLETE LIST OF SEQUENCES EXPERIMENTS 1 AND 2

Learning Sequences		
121113	434523	411344
411352	43525	413452
41352	411113	1235
12555	1255	411352
413	12113	12344
123	121134	12134
123525	41344	435255
123523	41352	123452

Grammatical Test Sequences	Nongrammatical Test Sequences
121352	45343
4113	4513
12352	153322
123444	421515
413523	142
411134	4522
125	15342
4352	451213
413525	145133
434525	42153
121134	15312
1234	453

APPENDIX B
INSTRUCTIONS EXPERIMENT 1

Instructions were read out-loud by the RAs who ran the experiment. Additional instructions were presented on the computer screen that echoed those shown here.

Before Learning Section

Welcome! And thank you for your participation in this study. Before we begin, there are only a few things that I want to go over. First, you will be using a computer to view and hear sequences, made up of black boxes at different locations on the screen and different tones presented through headphones. During the experiment, please keep the headphones on at all times and keep your head in the headrest unless otherwise instructed. Secondly, the headrest is put in a specific position and should not be moved. Please, try not to move the headrest. The experimenter (that's me) may have to adjust the headrest, but you should never move the headrest yourself. Finally, there will be two major sections to the experiment. You will complete both of them on the computer. Once you've finished the first section, you will be asked to alert the experimenter. When you read this on the computer, please alert me that you are ready to receive further instruction and I will be there to assist you as soon as I possibly can. We are going to wait until everyone is ready to begin the second section before moving on. Now, if you've read and signed the consent form and are ready to begin, please be sure that your cellphones are on silent (so that there are no interruptions during the study) and we will get started.

Before Testing Section

Great job! Now that you've all completed the first section, we will begin the second part of the study. As the instructions have already informed you, you will be doing something a little different this time. Instead of comparing the sequences to one another in this section, you will only get one sequence at a time during this part. You are being asked to compare each sequence in this section to ALL of the sequences from the first part of the study. If it seems like the sequence follows

the same rules (in other words, if it looks or sounds like it could have been in the first section of the study) then you will say it follows the same rules by pressing the red S. If you don't think that it seems like it came from the same set of rules (in other words, if it does not seem like it could have been in the first section of the study) then you will say that it follows a different set of rules by pressing the blue D.

Remember that this part of the study will have either image only or sound only sequences. Even though the sequences will not contain both the boxes and tones, they may still follow the same rules. Compare the image only sequences to the image part of the sequences from the first part of the study. Compare the sound only sequences to the sound only part of the sequences from the first section.

if you have to adjust the headrest do it now, ask them not to move the headrest once you have adjusted it.

Do you have any questions about this section of the experiment?

Please put your head in the headrest and begin the second section. This part should take about 20 minutes to complete. The image only and sound only parts of this section will be blocked; you will be told at the beginning of each block whether the sequences will be image or sound. You will get two blocks of each kind of sequence.

When you are done with this section, I will have a few questions for each of you. I will want to talk to you one at a time, so if I'm with someone else please wait until I am free. I will be with you as soon as I can.

End of Experiment

Great!

Thank you for your participation. If you have any questions, I will be happy to answer them now.

APPENDIX C
INSTRUCTIONS EXPERIMENT 2

Instructions were presented both on the screen and read out-loud over the headphones. Two versions of the instructions were needed, due to the two learning phase conditions. Alternating instructions are shown in brackets.

Before Learning Section

Welcome! Thank you for your participation. Today, you are going to be [viewing/viewing and hearing] some sequences on this computer. The sequences will be made up of a little black box that will appear at one of 5 locations on the screen. Those locations are the 4 corners and the center of the screen.

[The boxes will be accompanied by one of 5 tones, so that a sequence will be made up of "beeping boxes"]

Sequences will be anywhere from 3 to 6 [boxes/beeping boxes] in length. Sequences will always come in pairs. Before the first sequence in a pair plays, you will see a plus sign in the center of the screen. Following the end of the first sequence, the plus sign will appear again briefly. Then the second sequence will play automatically.

Your job is going to be to decide if the first and second sequences in the pair were the same as one another. If they are the same, then the same [boxes/beeping boxes] will appear in the same locations, in the same order. Following the second sequence in each pair, a prompt will show up on the screen that says "Same?" and it is your job to answer "Same" if the two sequences matched or "Different" if the first and second sequence in the pair did not contain the same [boxes/beeping boxes] in the same order.

You will press the key marked with a Red "S" on the keyboard to indicate that the two sequences are the same. You will press the Blue "D" to indicate that the two sequences are different.

After you answer "same" or "different" the next pair of sequences will automatically begin to play. You will repeat this process until I tell you that you are finished, at which point I will ask you to alert your RA.

Please remember to keep your head in the chinrest with your nose facing toward the star on the wall in front of you. Sit up and sit forward. You may move your eyes but not your neck.

Also, please remember to keep the headphones on at all times.
Altogether, this section should take about 15-20 minutes to complete. Following this section there will be one more, very short section before you are all done.

If you have any questions, please ask the RA at this time.

If you are ready to begin, please press the spacebar at this time.

Thank You

After Learning Section

Well done! You have finished comparing all of the pairs of sequences! Now you are ready to move on to the final section of the study. Please tell the RA at this time that you are ready to move on.

Before Testing Section

Welcome back! This is the final part of the study, and it will not take very long to complete.

But, before you can start this section, I've got to let you in on a little secret.

Even though you were not told this before, all of the sequences from the first section of this study were made by this computer using a complex set of rules. The rules allowed the computer to make many different sequences that all followed the same underlying patterns.

These complex rules told the computer which [boxes/beeping boxes] were allowed to follow one another within a single sequence. That means that there were certain [box locations/beeping boxes] that often occurred back to back within the sequences, and that certain [box locations/beeping boxes] never occurred next to one another within a single sequence.

What does that mean to you?

In this section you will be viewing some brand new sequences and deciding whether or not these new sequences follow the same rules as all of the sequences from the first section.

Keep in mind that even if two sequences within a pair did not match one another in the first part of this study, both of those sequences followed the rules because ALL sequences in the first section followed the rules.

Here is what to expect:

[First, unlike the first part of this study, there will not be any more beeps. You will see the boxes but not hear them. Despite this, they could still follow the same rules in regard to the location of the boxes on the screen.]

You will see one new sequence at a time in this section. It is new, because you have never seen this exact sequence before. For each new sequence, you must decide if it either follows the same rules (which means that it would contain the same sort of patterns) or if the new sequence breaks the rules at some point (which means it does not contain the same patterns). Remember: You are comparing each new sequence to ALL of the sequences from the first section of this study.

Following each new sequence a prompt will appear that says "Same Patterns?" If you think that the computer used the same rules as before, then you will press the Red "S". If you think that the computer used a different set of rules, you will press the Blue "D".

Half of the new sequences will follow the same rules, and so will be the same. Half of the new sequences will break the rules at some point, and so will be different.

If you do not know whether or not the computer used the same rules, go with your best guess! It's okay if you cannot describe the rules. Honest guesses are always welcome!

Please remember to keep your head in the chinrest with your nose facing toward the star on the wall in front of you. Sit up and sit forward. You may move your eyes but not your neck.

Also, please remember to keep the headphones on at all times.

This section should only take about 10 minutes to complete. I will let you know when you are done.

If you have any questions, please ask the RA now.

If you are ready to begin, please press the spacebar at this time.

Thank you!

End of Experiment

Great job! You are all done. Please tell the RA that you've finished, and have a great day!