BRIEF REPORT

Tasks determine what is learned in visual statistical learning

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Abstract Visual statistical learning (VSL), the unsupervised learning of statistical contingencies across time and space, may play a key role in efficient and predictive encoding of the perceptual world. How VSL capabilities vary as a function of ongoing task demands is still poorly understood. VSL is modulated by selective attention and faces interference from some secondary tasks, but there is little evidence that the types of contingencies learned in VSL are sensitive to task demands. We found a powerful effect of task on what is learned in VSL. Participants first completed a visual familiarization task requiring judgments of face gender (female/male) or scene location (interior/exterior). Statistical regularities were embedded between stimulus pairs. During a surprise recognition phase, participants showed less recognition for pairs that had required a change in response key (e.g., female followed by male) or task (e.g., female followed by indoor) during familiarization. When familiarization required detection of “flicker” or “jiggle” events unrelated to image content, there was weaker, but uniform, VSL across pair types. These results suggest that simple task manipulations play a strong role in modulating the distribution of learning over different pair combinations. Such variations may arise from task and response conflict or because the manner in which images are processed is altered.

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Perceptual systems face two severe challenges: the inverse problem of determining causes from noisy inputs, and capacity limitations. One proposed coping mechanism is to chunk information that consistently co-occurs spatially or temporally. When acquired in an unsupervised manner, this is called “statistical learning” (SL). This phenomenon happens in infants (Saffran, Aslin, & Newport, 1996) and adults (Saffran, Johnson, Aslin, & Newport, 1999), who acquire and flexibly express learning of such contingencies across sensory domains. Demonstrations of *visual* SL (VSL) are prevalent for spatial (Fiser & Aslin, 2001, 2002b) and temporal (Fiser & Aslin, 2002a) contingencies. Temporal VSL permits recognition of stereotyped sequences following exposure. Learning effects are observed in explicit recognition rates as well as enhanced performance (Turk-Browne, Jungé, & Scholl, 2005).

VSL seems to occur without explicit awareness of contingencies present during familiarization. Thus, VSL is usually studied using minimal, unvarying demands during learning, and little is known about resource requirements and task interactions with VSL. Prior work probed relationships between temporal VSL and selective attention. Turk-Brown, Jungé, and Scholl (2005) found that participants viewing a stream of bicolored objects selectively learned the *attended* color stream, suggesting that selective attention “gates” VSL (but see Musz, Weber, & Thompson-Schill, 2015). Pursuing a different hypothesis regarding shared mechanisms between VSL and statistical summary formation, Zhao et al. (2011) showed that statistical summary tasks performed during familiarization disrupted VSL compared with a nonsummary task. A follow-up suggested that this may be due effects on focal

attention and working memory (Hall, Mattingley, & Dux, 2015). These findings suggest that VSL is likely sensitive to familiarization task demands, although both effects could be due to changes in the distribution of selective attention within the sequence.

Is VSL subject to other forms of interference? VSL is correlated with caudate activity (Turk-Browne, Scholl, Chun, & Johnson, 2009), which also is implicated in response selection and task-set switching (Cools, Clark, & Robbins, 2004; Crone, Wendelken, Donohue, & Bunge, 2006; Seger, 2008). Stevens et al. (2015) demonstrated that concurrent motor activity disrupts VSL compared with passive familiarization. They concluded that coordinated motor activity and extraction of statistical regularities rely on common resources. The role of the caudate in stimulus-response learning motivated us to test whether VSL is affected by simple response and task requirements during familiarization.

An additional question relevant to this work is whether stimulus similarity plays a role in VSL. Most prior research has employed homogenous stimuli, e.g., abstract shapes. Several paired faces and scenes (Turk-Browne, Scholl, Johnson, & Chun, 2010) but did not compare within-category to cross-category performance (although statistical relationships among conceptual categories can support SL-like recognition; Brady & Oliva, 2008).

The present study

We asked how changes in task or response modulate VSL. Surprisingly, there were robust effects of simple response-selection demands, such that the mapping of paired stimuli to the same or different responses during training had a significant effect on subsequent recognition (Experiments 1–2). A less reliable effect of task-switching also emerged, with weaker learning for cross-category compared to within-category pairings. Experiment 3 demonstrated that there is no notable influence of categorical similarity on VSL in the absence of varying training task demands. Experiment 4 randomly assigned participants to categorize or to detect jiggle events, finding deleterious effects of both task and response switching on VSL selective to the categorization group. Familiarization task demands affect VSL, affecting not only the overall strength of learning, but also the distribution of learning across types of stimulus combinations.

General methods

Methods jointly summarize 4 experiments. All procedures were approved by the University of Delaware's Institutional Review Board.

Participants Participants (Experiment 1: $N = 20$, Experiment 2: $N = 30$, Experiment 3: $N = 25$) were University of Delaware undergraduates and recruited online via Amazon Mechanical Turk (Experiment 4: $N = 104$), reporting normal or corrected-to-normal visual acuity and color vision. They were compensated with course credit or cash and provided informed consent.

Apparatus Experiments 1–3 employed Linux PCs with 17" CRT monitors (resolution: 1,280 x 1,024 at 75 Hz), operating MATLAB 2015a (Mathworks; Natick, MA) with Psychophysics Toolbox 3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). Participants sat ~54 cm from the screen and responded via keyboard. Experiment 4 employed the participant's web browser and computer using jsPsych 5.0.3 (de Leeuw, 2015) and Psiturk (Gureckis et al., 2016).

Stimuli Face images were derived from the FERET database (Phillips, Wechsler, Huang, & Rauss, 1998) and were cropped to minimize background. Scene photos were collected from the Internet and depicted interior and exterior scenes. Images were 200 x 200 pixels (approximately $5.3^\circ \times 5.3^\circ$).

Procedures Participants completed a familiarization phase followed by a surprise recognition phase in 1-hour sessions.

Familiarization phase Before familiarization, 16 *AB* pairs of images (32 "paired" images) were randomly predetermined (Figure 1a): *A* always preceded *B* during familiarization. Pairs were determined such that there was one of each unique combination of female, male, interior, and exterior (e.g., 4 pairs consisted of a different female (*A*), followed by (*B*) a female/male/interior/exterior image). For experiments 1–3, 16 unpaired "singleton" images also appeared (4 per image type). All images appeared 4 times per each of 5 blocks, each block 192 trials (Experiments 1–3; Figure 1b), and 128 trials (Experiment 4, which excluded singletons during familiarization). Sequences were pseudo-randomized so pairs never immediately repeated. Images appeared for 1 s with an ITI of 1 s. A yellow circular frame fixation marker was superimposed at the center, remaining present during the ITI.

For Experiment 1, participants classified images as female/interior using the "z" key and the left hand or male/exterior using the "m" key and the right hand. For Experiment 2, the sole difference was that "n" and "m" keys were used and participants used two fingers of one hand to verify that response effects did not depend on using different hands. We encouraged accuracy and fast responses, which were accepted within a 2-s interval of stimulus onset. Correct and error responses resulted in turning the fixation marker green or red, respectively, until the end of the ITI.

In Experiment 3, participants monitored images and pressed the space bar when an image "flickered." For 25%

Figure 1. (a) Example AB pairings for one subject. Not shown: 16 singleton items (4 of each type) that were not predictive or predictable in the training sequence (singletons did not appear in Experiment 4). (b) Sample trial sequence from the training sequence. Colored outlines are intended to depict the class of the pair, and were not shown to subjects. Each image appeared for 1 s and ISI was 1 s. A yellow fixation circle appeared overlaid on images and during ISI period (not depicted). The

circle turned green after a correct response, red after an incorrect response. Trials after the first trial in the block were classified according to their relationship to the prior trial (Same/Different task, and Same/Different response required) and their membership (or not) in a paired set, which made them unpredictable or predictable. (c) Example of a recognition-stage trial.

of image presentations, the image briefly turned off (53.3 ms) after 453.3 ms. Responses occurring until the following stimulus onset were hits.

In Experiment 4, participants were randomly assigned to groups. The categorization group performed the task described in Experiment 1, except mappings of male/female and indoor/outdoor to the “z” and “m” keys were randomized across participants. The detection group monitored streams of images for “jiggle” events, occurring once per image per block, and pressed space when jiggle occurred. Jiggles occurred in nonadjacent pairs and began 300 ms after image presentation with 2 cycles of displacement 5 pixels left/right of center, each cycle taking 200 ms. Participants received more feedback (e.g., “Error – press Z key for outdoor, M key for indoor”; 3,000 ms) to account for possible inattention during instructions. Participants completed a practice familiarization phase of 32 trials with images that were not reused.

Recognition phase The recognition phase consisted of 64 forced-choice trials in which a target pair was matched

against a foil pair (presented with same timing as familiarization and preceded by a 0.5-s sequence number label followed by a 0.5-s blank). Participants were informed before this phase about AB pairs and indicated which sequence had appeared during familiarization. Trials were self-paced, responses unspeeded, and no feedback was provided.

Foil pairs had the same composition as targets but were recombined A and B items. The A and B images in foil pairs remained consistently in the A or B position but were swapped across pairs. All target and foil pairs appeared four times during the Recognition Phase.

Exclusion criteria S6 We excluded from analysis participants with familiarization accuracy <80% (Experiments 1–2, Experiment 4 categorization group) or a false-alarm/miss rate >20% during familiarization (Experiment 3, Experiment 4 detection group). One participant was excluded from Experiments 1 and 2, and four were excluded from Experiment 3. In Experiment 4, two were excluded from the categorization group, and none from the detection group.

Experiment 1

Experiment 1 examined whether VSL depends on response and task demands. AB pair images relied on the same or different task sets and responses (StSr, StDr, DtSr, and DtDr; the first letter indicates same/different task—scene or face classification—and the second letter indicates same/different response; Figure 1a).

If response demands interfere with VSL, then pairs with the *same* response during familiarization (StSr, DtSr) should elicit superior recognition compared to pairs requiring different responses (StDr, DtDr). If executive demands matter, then same task pairs (StSr/StDr) pairs should be easier to learn than cross-task pairs (DtSr/DtDr). Similar effects might manifest if subcategorical and/or categorical distinctions influence learning, a possibility addressed in Experiments 3 and 4.

Results

Familiarization phase We observed no effects of learning on performance ($ps > 0.29$). There were effects on RTs of trial transition type (Figure 2a). Participants were slowed by two conditions: response switches ($p = 0.006$, e.g., female→male) and task switches ($p = 0.01$; e.g., male→outdoor), implying switching costs. For additional details see [Supplementary Materials](#).

Recognition phase To assess learning, we compared recognition for each pair type (defined by training conditions: StSr/StDr/DtDr/DtSr) to chance (50%) using one-sample t -tests with Bonferroni correction ($\alpha = 0.05/4 = 0.0125$). Participants performed above-chance at recognizing StSr ($t(18) = 4.98$, $p < 0.001$, $d = 1.14$), and DtSr pairs ($t(18) = 3.05$, $p = 0.007$, $d = 0.70$). Recognition for StDr ($t(18) = 2.02$, $p = 0.058$, $d = 0.46$) and DtDr ($t < 1$) pairs did not differ from chance.

To compare learning across response and task, we conducted a 2 (response) $\times$ 2 (task) repeated-measures ANOVA on accuracy. There was a significant main effect of response ($F(1,18) = 12.3$, $p = 0.002$, $\eta_p^2 = 0.41$), such that same-response were better recognized than different-response pairs. The main effect of task approached significance ($F(1,18) = 4.28$, $p = 0.053$, $\eta_p^2 = 0.19$); same-task pairs were better recognized than different-task pairs. There was no interaction ($F < 1$). A t -test contrasting DtSr with DtDr pairs provided direct evidence that switching responses across items of the pair impaired learning ($t(18) = 2.46$, $p = 0.025$, $d = 0.56$).

Discussion

During familiarization, task and response switching slowed responses. At recognition, participants performed above-

chance when responses did not change. This suggests that the nature of pairings mattered and that maintaining the same response across a pair benefited subsequent recognition.

Experiment 2

Experiment 2 was a replication of Experiment 1, with higher power to elucidate borderline effects of task demands on VSL. We tested 30 participants based on a power analysis, suggesting that this sample would exceed 95% chance of detecting the task effect measured in Experiment 1.

Results

Familiarization stage As in Experiment 1, responses were slower when response ($p = 0.03$) or task ($p = 0.02$) switched (see Figure 2c and [Supplementary Materials](#) for further details).

Recognition stage Participants recognized StSr ($t(28) = 5.11$, $p < 0.001$, $d = 0.95$) and DtSr ($t(28) = 3.03$, $p = 0.005$, $d = 0.56$) pairs significantly above chance (corrected $\alpha = 0.0125$), but performance did not differ from chance for StDr ($t(28) = 1.92$, $p = 0.065$, $d = 0.36$), or DtDr pairs ($t(28) = 0.78$, $p = 0.44$, $d = 0.14$; Figure 1d).

An ANOVA revealed a main effect of response during familiarization, as in Experiment 1, ($F(1,28) = 10.4$, $p = 0.003$, $\eta_p^2 = 0.27$). The main effect of task showed a numerical but nonsignificant trend, such that pairs involving task switches were less recognizable ($F(1,28) = 2.30$, $p = 0.14$, $\eta_p^2 = 0.08$). There was no interaction ($F < 1$). We return to the question of whether task switches impair pair learning in Experiment 4.

Discussion

Experiment 2 replicated Experiment 1. During familiarization, response switches slowed reaction times. During recognition, those pairs acquired with consistent responses showed evidence of VSL. A weaker task switch penalty did not reach statistical significance. We reasoned that familiarization task demands interfered with VSL, particularly response switching. An alternative explanation could be that VSL is more effective for pairs with higher inter-item similarity. This possibility is addressed below.

Experiment 3

This experiment minimized familiarization task demands and ensured consistent responses across pair types. The

Figure 2. (a and c) Mean RTs from Experiment 1. Two familiarization stages averaged over blocks 2-5. (b and d) Mean correct recognition rates for the recognition stage for Experiments 1 and 2, respectively, separated

categorization task was replaced with flicker detection to ensure sustained attention. If response and task demands explained the pattern of selective VSL in Experiments 1 and 2, then removing them should equalize VSL across learning conditions. In Experiment 3, we maintained the same terminology and classification (StSr/StDr/DtSr/DtDr) to facilitate comparisons with Experiments 1-2, although DtSr and DtDr distinctions were arbitrary in this context. A sample size of 20 was planned, because this experiment was followed and designed to match Experiment 1, but 26 were collected due to accidental oversampling.

Results

Familiarization phase (Flicker Detection) Performance accuracy was high (mean false-alarm rate: 0.8%; mean miss rate: 4.7%). We neither anticipated nor observed variation in accuracy or RT as a function of trial type given the simple detection task.

Recognition phase All pair types were recognized at above-chance levels (SS: $t(20) = 3.53, p = 0.002, d = 0.77$; StDr: $t(20) = 2.47, p = 0.023, d = 0.54$; DtSr: $t(20) = 2.70, p = 0.014, d = 0.59$; DtDr: $t(20) = 3.21, p = 0.004, d = 0.70$; Figure 3), although StDr and DtSr did not pass Bonferroni correction ($\alpha = 0.0125$). A 2 x 2 ANOVA revealed no main effects of category or subcategory ($F < 1$) and no interaction of category and subcategory, ($F(1,20) =$

1.19, $p = 0.29, \eta_p^2 = 0.06$). No pairwise differences between conditions approached significance ($p_s > 0.2$).

Discussion

When the familiarization task was trivial, pairs showed statistically equivalent VSL. On the basis of this finding, we hypothesized that interference effects observed in Experiments 1-2 were likely due to task demands during familiarization.

Experiment 4

Our results suggest that response, and possibly task, demands influence what is learned in VSL. Yet, this interpretation

Figure 3. Recognition rates for Experiment 3

Figure 4. Mean RTs from familiarization stage for the categorization group of Experiment 4, averaged over blocks 2-5

requires comparisons across experiments. Experiment 4 compared a categorization with a detection task in a larger sample. We pseudo-randomly assigned participants to two equal-sized groups, one that completed a categorization task and another detected “jiggle” events during familiarization.

Results

Familiarization phase As expected, the Detection group who pressed a key when the shape “jiggled” was highly accurate (mean false-alarm rate: 1.0%; mean miss rate: 1.8%) and not significantly influenced by image type or predictiveness.

The Categorization group showed main effects of both task ($p = 0.002$) and response ($p = 0.003$). There was an interaction due to the subadditivity of those factors ($p < 0.001$; Figure 4; [Supplementary Materials](#)).

Recognition phase As in Experiment 3, and to maximize comparability across groups, we separated Detection outcomes into StSr, StDr, DtSr, and DtDr bins, although the DtSr/DtDr distinction was arbitrary. We randomized

assignment of image type to “response key” for the Detection group to equate distinctions across group assignment.

To identify significant group interactions, we conducted a mixed-effects ANOVA on accuracy at recognizing familiarized pairs, with the between-subjects factor of group, and task and response (same or different) as repeated-measures factors (Figure 5). Interactions of group $\times$ response ($F(1,100) = 15.2$, $p < 0.001$, $\eta_p^2 = 0.13$), and group $\times$ task ($F(1,100) = 7.27$, $p = 0.008$, $\eta_p^2 = 0.068$) reached significance. To understand these interactions, we conducted two follow-up repeated-measures ANOVAs for each group separately.

For the Categorization group, results were similar to Experiments 1 and 2, albeit with significant task effects. One-sample t -tests comparing performance to chance recognition rates showed that *only* DtSr and StSr conditions exceeded chance ($t(49) = 3.13$, $p = 0.003$, $d = 0.44$; and $t(49) = 7.01$, $p < 0.001$, $d = 0.99$, respectively). The 2×2 ANOVA revealed a main effect of task was significant ($F(1,49) = 6.24$, $p = 0.016$, $\eta_p^2 = 0.11$); a task switch was associated with poorer subsequent memory, as was a response switch ($F(1,49) = 24.1$, $p < 0.001$, $\eta_p^2 = 0.33$). Finally, the interaction was just significant ($F(1,49) = 4.04$, $p = 0.05$, $\eta_p^2 = 0.076$), due to under additivity of task and response effects.

In contrast, the Detection group had significantly above chance recognition rates for DtDr and DtSr ($t(51) = 3.65$, $p < 0.001$, $d = 0.51$ and $t(51) = 3.00$, $p = 0.004$, $d = 0.42$). StDr ($t(51) = 1.93$, $p = 0.06$, $d = 0.27$) and StSr ($t(51) = 2.06$, $p = 0.045$, $d = 0.29$) were not significant following multiple-comparisons correction. A repeated-measures ANOVA revealed no significant main effects or interaction.

We contrasted group performance in the four conditions with independent samples t -tests. The groups significantly differed in StSr performance ($t(100) = 3.38$, $p = 0.001$, $d = 0.67$), with better performance in the Categorization group, and the DtDr difference was trending ($t(100) = -1.72$, $p = 0.088$, $d = -0.34$), favoring Detection group performance. Other differences were nonsignificant ($ps > 0.62$).

Figure 5. Experiment 4: recognition phase accuracy.

Discussion

Experiment 4 provided evidence showing that the familiarization task influences what contingencies are learned. The passive, jiggle-detection familiarization task yielded more consistent learning across conditions. The Categorization group showed reduced learning in conditions that involved a task and/or response switch.

General discussion

VSL depends on the familiarization task and on what types of statistical contingencies are learned. We found VSL disruption when stimulus categories were associated with different response sets and responses. Response-shift effects were more robust than task-shift effects, but both interfered with VSL. Importantly, VSL was *undifferentiated* among similar transitions under passive-viewing familiarization. Our results suggest that VSL operates equally well over similar and diverse stimuli when those combinations are familiarized under a passive task that does not confound response and task set differences with image content.

Why did task and response differences influence VSL recognition? Several possibilities deserve future investigation. We favor the interpretation that response and task selection demands interfere with acquisition. Even though switching response or task set imposed modest demands, consequences were evident in RTs during familiarization. VSL may rely, in part, on the mechanisms that support managing these sets; when demands on those mechanisms increase, learning suffers.

Alternatively, categorization task demands might have altered stimulus processing. For instance, the requirement to press a specific key in response to a female face may create a multimodal representation, including the action and the face image. Similarities and differences across such representations might influence what is more or less likely to be learned. The removal of such contingencies at recognition may limit the expression of learned contingencies. Relatedly, the inclusion of categorical judgments may create event boundaries. Boundaries induced by semantic processing are known to influence subsequent order judgments, with better order memory “within” event boundaries (DuBrow & Davachi, 2013).

Might these results reflect variations of selective attention, thought to play a role in SL (Saffran, Newport, Aslin, Tunick, & Barrueco, 1997; Turk-Browne, et al. 2005; Musz et al., 2015)? Our demonstrations were not based on dual-task procedures. Because interference occurred in the context of a task that required more than passive viewing, the results are unlikely attributable to simple variations in the overall strength of selective attention. Speculatively, categorization may have drawn selective attention to different features that the

detection task or it may have fluctuated under more demanding conditions of switches.

Our findings are consistent with observations of motor activity disrupting VSL (Stevens et al., 2015). Our data further suggest that interference effects may be due to response and task selection resources that may be critical to VSL. Our findings also make sense in light of neuroimaging data, suggesting that VSL is correlated with striatal activity (Turk-Browne et al., 2009), a neural correlate of other forms of motor-related and categorical learning (Cincotta & Seger, 2007; Rauch et al., 1997).

VSL may be multiple dissociable phenomena. Bays, Turk-Browne, and Seitz (2016) provided evidence that recognition and performance effects may be dissociable. We assessed learning by asking people to make judgments of familiarity. Other components of VSL may be inaccessible to report. Although we tried to access performance effects of learning during familiarization, we were largely unsuccessful. A different kind of transfer task, such as memory search through a temporal stream, might provide evidence of VSL where explicit recognition judgments fail, a possibility worth further investigation.

Conclusions

VSL is subject to multiple forms of interference. We found that different familiarization tasks produced different patterns of learning. Our findings highlight the fact that VSL is sensitive to the attention paid to stimuli during learning, and VSL manifests differently for different types of stimulus combinations depending on the task required.

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