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RESEARCH ARTICLE

Figures and figure supplements

Statistical learning attenuates visual activity only for attended stimuli

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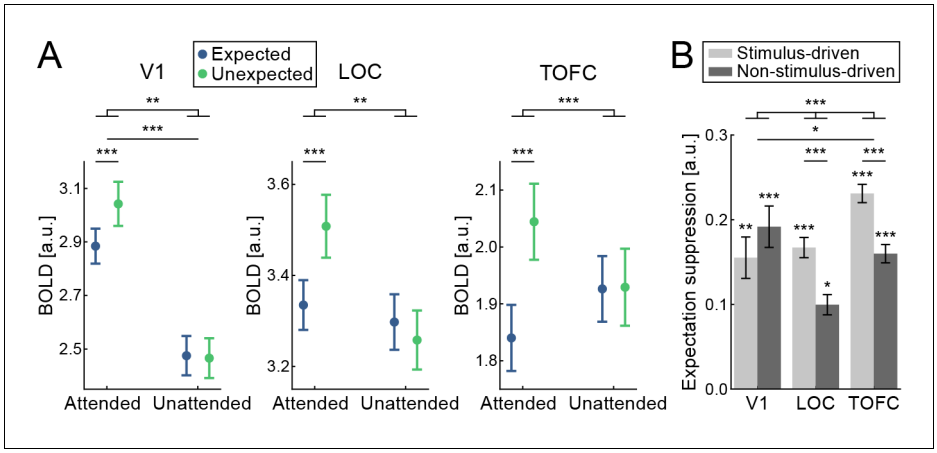

Figure 1. Expectation suppression within the ventral visual stream depends on attention. (**A**) Displayed are parameter estimates + /- within subject SE for responses to expected (blue) and unexpected (green) object stimuli during the objects attended task (attended) and objects unattended task (unattended). In all three ROIs, V1 (left), LOC (middle), and TOFC (right) BOLD responses were significantly suppressed in response to expected stimuli during the objects attended task. No difference was found between BOLD responses to expected and unexpected stimuli during the objects unattended task. The interaction effect between expectation and attention condition was significant in all three ROIs. (**B**) Expectation suppression in primary visual cortex is stimulus unspecific, and specific only in higher visual areas. Displayed is the average expectation suppression effect (BOLD responses, unexpected minus expected) split into stimulus-driven (light gray) and non-stimulus-driven (dark gray) gray matter voxels. Data are shown for the three ROIs, V1 (left bars), LOC (middle bars), and TOFC (right bars). Expectation suppression in LOC and TOFC was significantly larger for stimulus-driven than non-stimulus-driven voxels, while no such difference was evident in V1, indicating that expectation suppression in V1 was stimulus unspecific. Error bars indicate within-subject SE. Note, that the ROI masks in panel A and B differ, for details see: *ROI definition* and *Stimulus specificity analysis* in the Materials and methods section. *p<0.05. **p<0.01. ***p<0.001.

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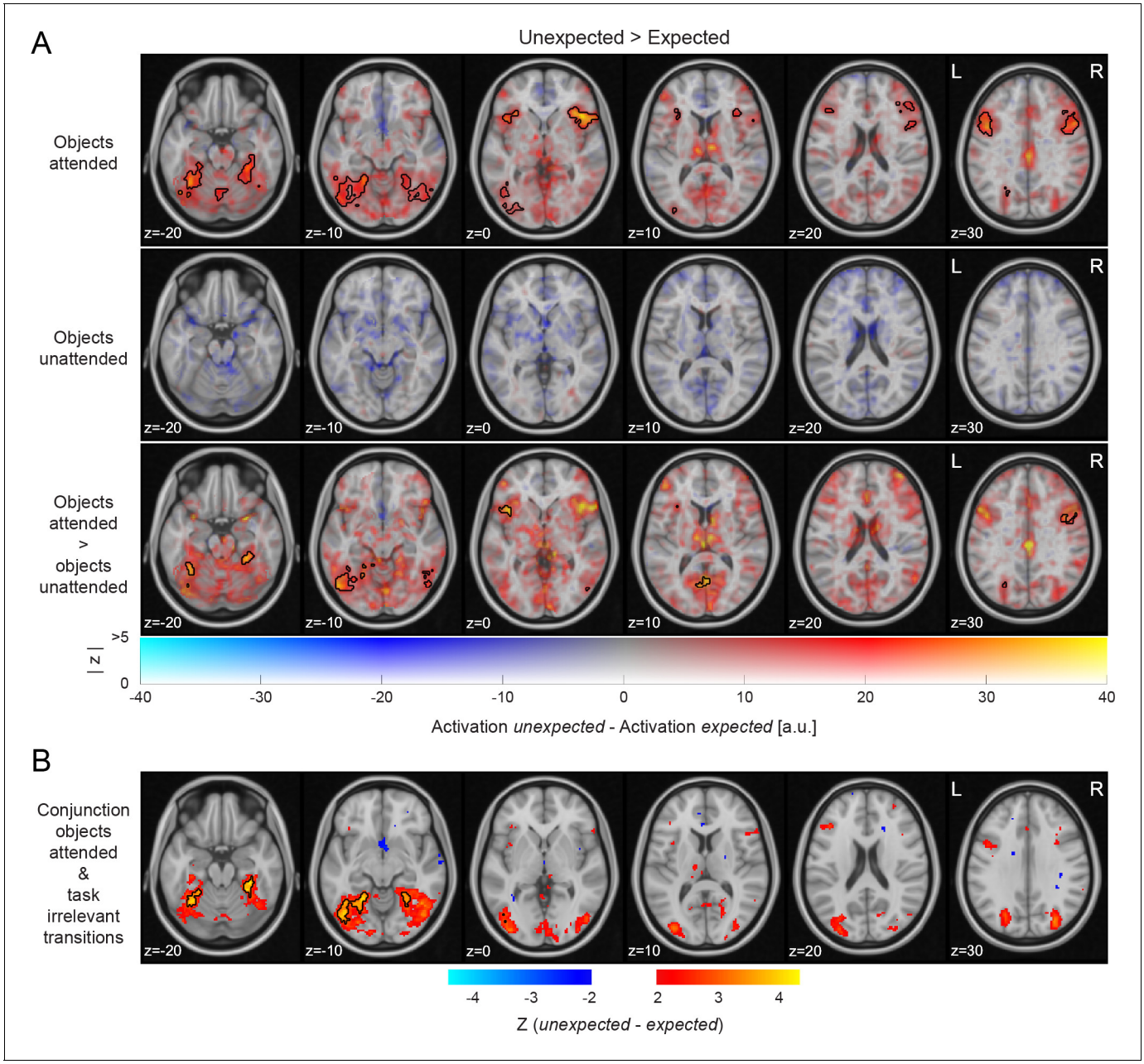

Figure 2. Expectation suppression across cortex for attended object stimuli only. (**A**) Widespread expectation suppression across cortex in the objects attended condition. Displayed are parameter estimates for unexpected minus expected image pairs overlaid onto the MNI152 2 mm template. Color indicates unthresholded parameter estimates: red-yellow clusters represent expectation suppression. Opacity represents the z statistics of the contrasts. Black contours outline statistically significant clusters (GRF cluster corrected). Significant clusters included major parts of the ventral visual stream (early visual cortex, LOC, TOFC), anterior insula, and inferior frontal gyrus during the objects attended condition (upper row). No significant clusters were evident in the objects unattended condition (middle row). The interaction (attended >unattended; bottom row) showed significant clusters similar to those of the attended condition, albeit less extensive. (**B**) Expectation suppression across the ventral visual stream for attended objects, but with task-irrelevant predictions. Displayed are z statistics of the contrast unexpected minus expected of the conjunction: *attended task-relevant predictions* $\bigcup$ *task-irrelevant predictions*; data of task-irrelevant predictions from ***Richter et al. (2018)***. Exclusively the ventral visual stream clusters showed significant expectation suppression in this conjunction, while all non-sensory area clusters were no longer significant. Thus, only the ventral visual stream clusters displayed a sensitivity to conditional probabilities, irrespective of whether predictions were task-relevant or task-irrelevant, as long as the predictable stimuli were attended.

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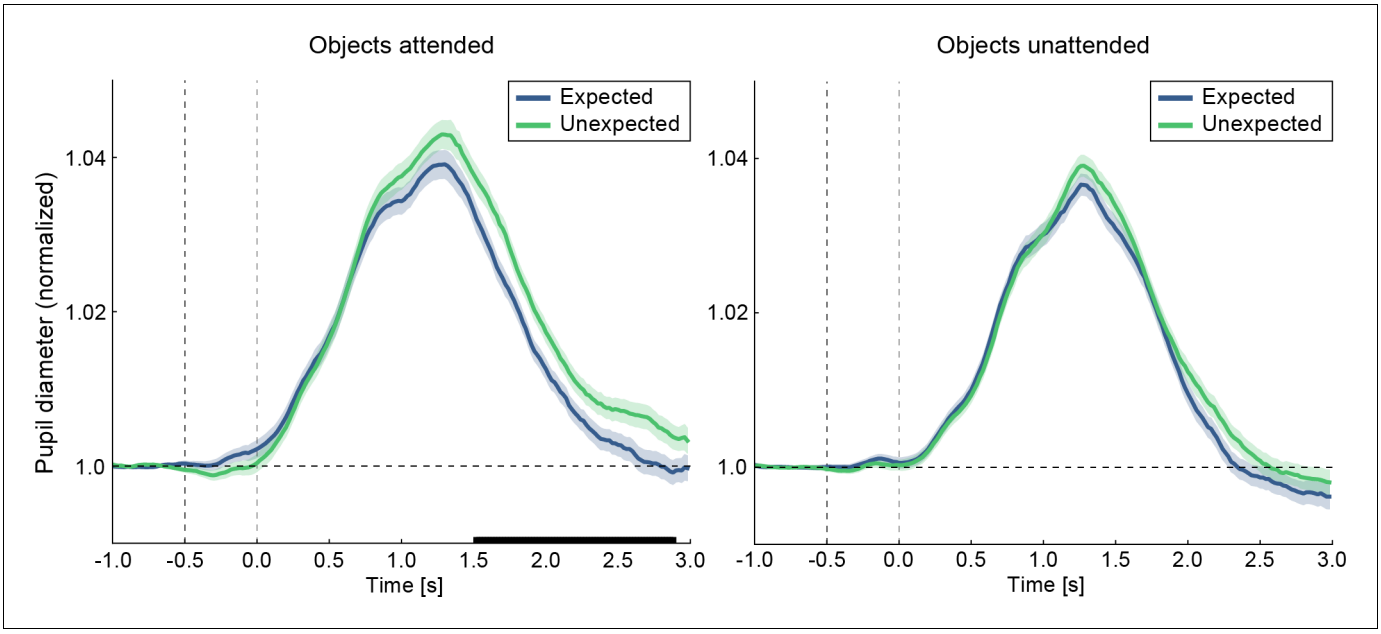

Figure 3. Larger pupil dilations in response to unexpected compared to expected stimuli during the objects attended task. Displayed are pupil diameter traces over time, relative to trailing image onset. Pupil diameter data for expected (blue) and unexpected (green) image pairs are shown for the objects attended task (left) and objects unattended task (right). The black line on the abscissa denotes statistically significant differences in pupil dilations between expected and unexpected images (cluster permutation test, $p<0.05$). In the objects attended condition significantly larger pupil dilations in response to unexpected images are evident between 1.52 to 2.88 s after trailing image onset (left). No significant difference is found in the objects unattended condition (right), nor in the interaction between conditions. The first vertical dashed line indicates leading image onset, the second vertical line trailing image onset. Shaded areas denote within-subject SE. Timepoints from −1.0 to −0.5 s served as baseline period.

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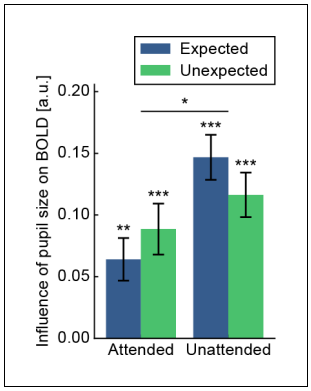

Figure 3—figure supplement 1. Pupil dilation influences BOLD responses in V1. Displayed are the parameter estimates of the influence of pupil size on BOLD responses in V1. BOLD responses increase with larger pupil dilations regardless of whether stimuli were attended and expected. However, pupil dilation influenced BOLD responses more when objects were unattended than attended. Whether stimuli were expected or unexpected did not change the association between BOLD and pupil dilation. Error bars indicate within-subject SEM.

*p<0.05, **p<0.01, ***p<0.001.

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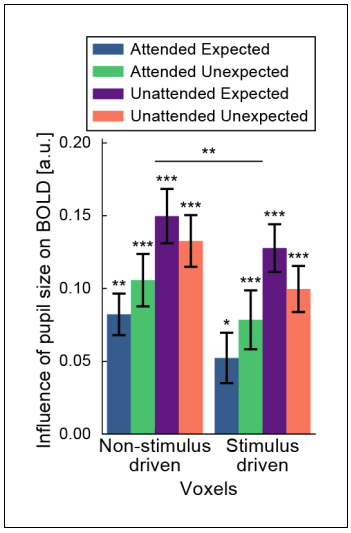

Figure 3—figure supplement 2. Pupil dilation influences BOLD responses more in non-stimulus-driven than stimulus-driven V1 voxels. Displayed are the parameter estimates of the influence of pupil size on BOLD responses in V1. BOLD responses increase with larger pupil dilation. This association was stronger in non-stimulus-driven (left) than stimulus-driven (right) V1 gray matter voxels. Error bars indicate within-subject SEM.

*p<0.05, **p<0.01, ***p<0.001.

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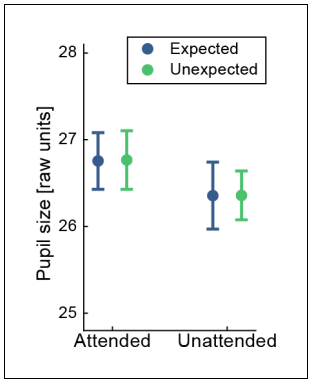

Figure 3—figure supplement 3. No difference in baseline pupil size between attention tasks, nor expectation conditions. Displayed are mean pupil sizes during the baseline period in raw units for expected and unexpected trials during the objects attended and unattended task. Pupil sizes during baseline were similar for trials with expected and unexpected object stimuli, as well as during both tasks. Error bars indicate within-subject SEM.

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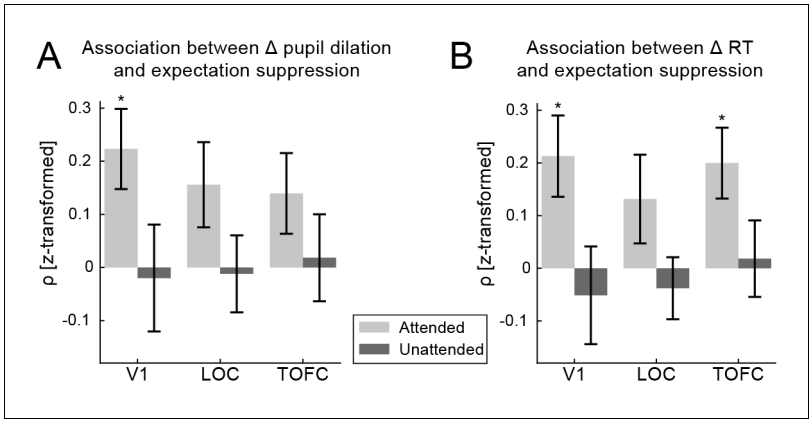

Figure 4. Expectation suppression is associated with pupil dilation differences and behavioral benefits of expectations. (**A**) Correlation of expectation suppression magnitude and pupil dilation differences due to expectation. When predictable objects are attended, trailing images that induce larger pupil dilation differences are also showing larger expectation suppression magnitudes in V1. No such association is evident when objects are unattended. (**B**) Correlation of expectation suppression magnitude and RT benefits due to expectation. When predictable objects are attended, larger RT benefits are associated with larger expectation suppression effects in V1 and TOFC. This association is absent when objects are unattended. Error bars indicate within-subject SEM. *p<0.05.

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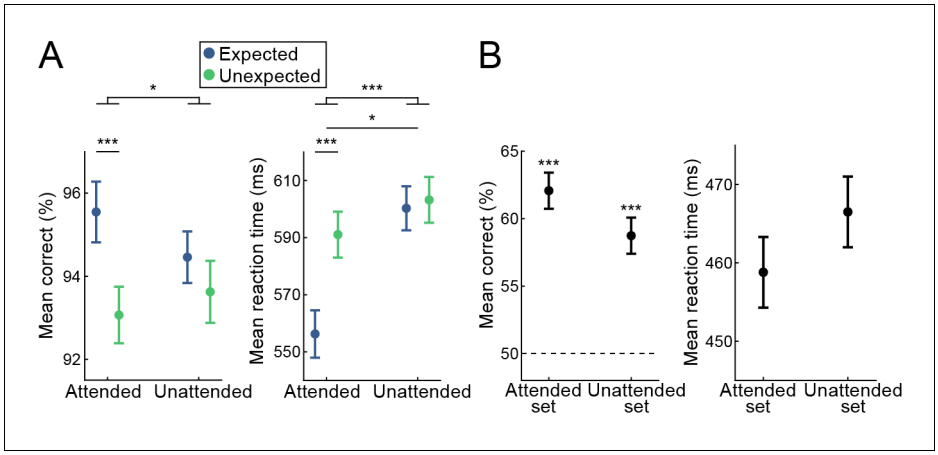

Figure 5. Behavioral results demonstrate statistical learning. (**A**) Behavioral benefits of expectations demonstrate statistical learning. Displayed are mean accuracy (left) and mean reaction time (right) + /- within subject SE. Responses to expected stimuli are significantly more accurate and faster, an effect exclusively observed during the objects attended condition. Thus, object identity expectations benefit behavioral performance during object classification and do not impact letter classification. (**B**) Pairs of both the objects attended image set and the objects unattended image set were classified significantly above chance, indicating a learning of the pairs for both conditions. Displayed are mean accuracy (left) and mean reaction time (right) during the post-scanning pair recognition task, + /- within subject SE. The dashed line indicates chance level. During the pair recognition task, no differences in either classification accuracy (left) or response speed (right) were observed between pairs previously belonging to the objects attended task compared to the objects unattended task. *p<0.05. ***p<0.001.

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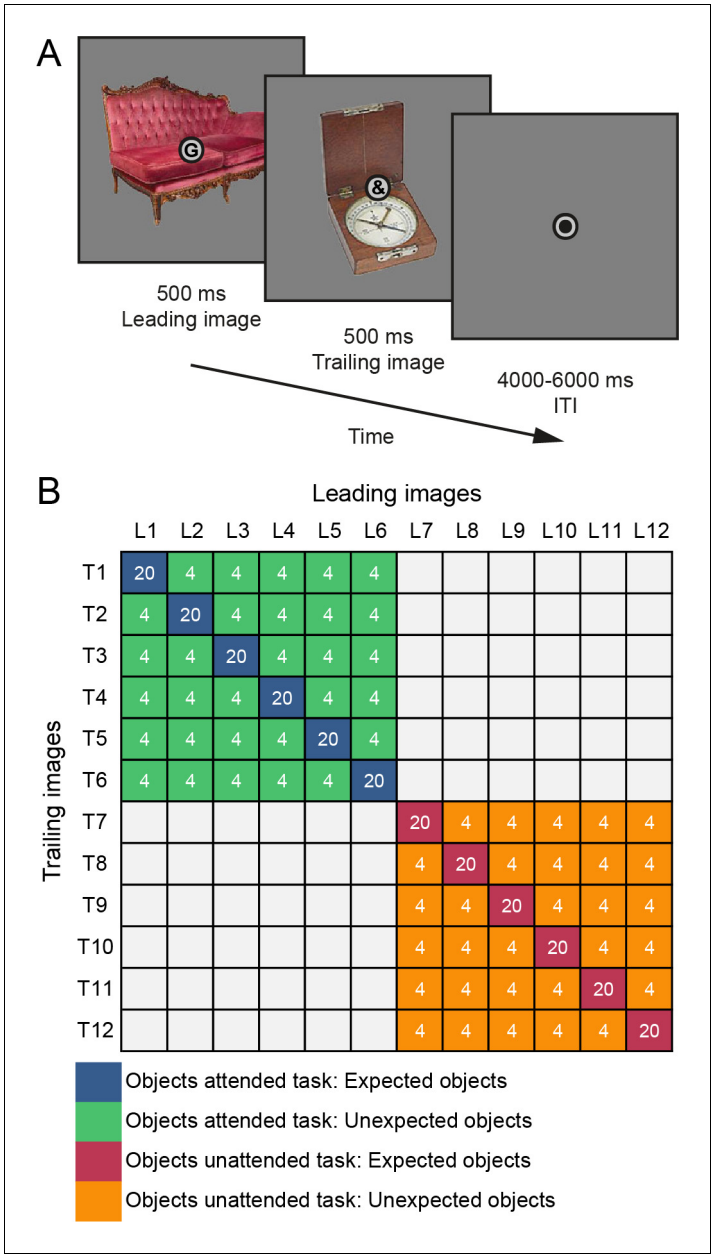

Figure 6. Experimental paradigm. (**A**) A single trial is displayed, starting with a 500 ms presentation of the leading object and the leading character superimposed at fixation. Next, without ISI, the trailing object and trailing character are shown for 500 ms. Each trial ends with a 4000–6000 ms ITI (MRI session; 1000–2000 ms ITI learning session), showing only a fixation dot. (**B**) Statistical regularities depicted as image transition matrix with object pairs and trial numbers during MRI scanning. L1 to L12 represent leading objects, while T1 to T12 represent the trailing objects. Leading and trailing objects were randomly selected per participant from a larger pool of images - that is, leading images of one participant may occur as trailing objects of another participant, in a different task, or not at all. Blue cells denote expected object pairs of the objects attended (object categorization) task, while green indicates unexpected object pairs of the objects attended task. Red denotes expected objects of the objects unattended (character categorization) task, and orange indicates unexpected objects of the objects unattended task. Each participant was also assigned 12 leading and 12 trailing characters (six letters, six symbols each). Unlike the object images, there was no association between leading and trailing characters – that is, the identity of the leading and trailing character was unpredictable. White numbers represent the total number of trials of that cell during MRI scanning. In total 120 trials of each of the four conditions were shown during MRI scanning per participant. In the behavioral learning session, participants performed an orthogonal oddball detection task,

Figure 6 continued on next page

Figure 6 continued

during which only expected pairs were shown (i.e., only the diagonal of the matrix), for a total of 80 trials per expected pair (960 trials total).

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