Perception, 2011, volume 40, pages 822 – 829

doi:10.1068/p6833

Probabilities in implicit learning

Philip Tseng, Tzu-Yu Hsu¶§, Ovid J L Tzeng¶§#, Daisy L Hung¶§, Chi-Hung Juan§‡
Institute of Cognitive Neuroscience, National Central University, 300 Jhongda Road, Jhongli City, Taoyuan County 32001, Taiwan; e-mail: tsengphilip@gmail.com; chijuan@cc.ncu.edu.tw;
¶ also Laboratories for Cognitive Neuroscience, National Yang-Ming University, Taipei 112, Taiwan;
§ also Institute of Neuroscience, National Yang-Ming University, Taipei 112, Taiwan; # also Institute of Linguistics, Academia Sinica, Taipei 115, Taiwan; ‡ also Institute of Network Learning Technology, National Central University, 300 Jhongda Road, Jhongli City, Taoyuan County 32001, Taiwan
Received 22nd September 2010, in revised form 20 June 2011; published online 22 August 2011

Abstract. The visual system possesses a remarkable ability in learning regularities from the environment. In the case of contextual cuing, predictive visual contexts such as spatial configurations are implicitly learned, retained, and used to facilitate visual search—all without one's subjective awareness and conscious effort. Here we investigated whether implicit learning and its facilitatory effects are sensitive to the statistical property of such implicit knowledge. In other words, are highly probable events learned better than less probable ones even when such learning is implicit? We systematically varied the frequencies of context repetition to alter the degrees of learning. Our results showed that search efficiency increased consistently as contextual probabilities increased. Thus, the visual contexts, along with their probability of occurrences, were both picked up by the visual system. Furthermore, even when the total number of exposures was held constant between each probability, the highest probability still enjoyed a greater cuing effect, suggesting that the temporal aspect of implicit learning is also an important factor to consider in addition to the effect of mere frequency. Together, these findings suggest that implicit learning, although bypassing observers' conscious encoding and retrieval effort, behaves much like explicit learning in the sense that its facilitatory effect also varies as a function of its associative strengths.

1 Introduction

Humans possess a remarkable intuition of patterns that take place. This intuition allows us to prioritise where to look at the right time and place. For example, crossing a traffic intersection requires one to look straight ahead for the traffic signal and left and right for oncoming vehicles, while filtering out other irrelevant stimuli that are also happening simultaneously. Since these patterns are stable over time and place (ie the locations of the traffic light and oncoming vehicles), knowledge of these regularities helps us navigate in our environment with ease. In the laboratory, such learning of spatial regularities can be studied systematically by measuring the time it takes to find a salient stimulus in a context that may or may not contain such regularity. One notable example of such learning is called contextual cuing (Chun and Jiang 1998; see also Fiser and Aslin 2001, 2002 for another form of implicit statistical learning).

Contextual cuing describes the learning and memory of the hidden regularity behind the surrounding visual context. The classic demonstration entails a visual-search paradigm where participants look for a rotated T among various rotated L-shaped distractors and make speeded responses about target orientation. Unbeknownst to the participants, some distractor layouts are repeated, and thus learning of these repeated contextual configurations, whether globally or locally, would provide a predictive cue to where the target is located (Jiang and Wagner 2004; Kunar et al 2006; Olson and Chun 2002). Chun and Jiang (1998) found that, as the experiment progressed, target-search reaction time (RT) in the repeated-context condition declined more rapidly than RT from the no-repeat condition. This indicated that their participants indeed had learned the pattern between certain distractor layout and the associated target location to increase search efficiency. Interestingly, this learning and usage of contextual guidance is implicit, as participants often fail to recognise the repeated distractor layouts, and are unable to guess the target location among its associated distractor layouts. Furthermore, memory of such visual context can facilitate search efficiency even after a 1-week delay (Chun and Jiang 2003), yet still leave no trace for conscious recognition. This line of research demonstrates that the visual system indeed can learn the hidden regularities of visual context to facilitate visual search, without subjective awareness.

Given the robust phenomenon of contextual cuing, one may ask whether implicit learning behaves the same as conscious learning. For example, can there be different rates of learning even though such learning is implicit? In other words, is some information implicitly learned better than others, thus creating a graded continuum of memory strength similar to explicit learning? If so, such continuous memory strength should vary as a function of the differing degrees in learning. This makes an interesting prediction as it implies that not only should people learn statistical regularities of their environment without being aware of it, but they should do so in a statistically optimal manner, such that highly probable events are learned more rapidly than less probable events. Alternatively, contextual information may be learned, but not expressed, if implicit facilitation requires learned information to pass certain memory threshold before it can be expressed to aid visual search. Given the implicit nature of contextual cueing, it is the perfect tool to answer such question. In this study, we varied the number of occurrences of each repeating visual context. Therefore, throughout the experiment, certain distractor configurations would be more probable than others, thus altering the degrees of exposure and learning between different distractor layouts. This is a novel manipulation in contextual-cuing research as all studies to date have only compared one frequency of repeating context with no repetition. Thus, whether the visual system can acquire different rates of probabilities simultaneously while maintaining such information below conscious threshold is still an open question. Visual-search studies have long manipulated probability of target locations (Geng and Behrmann 2002, 2005; Shaw and Shaw 1977), and observed that targets in likely locations are detected faster than targets in less likely locations. Studies of saccade latency also observed faster saccadic response towards highly probable target location, and vice versa (Carpenter 2004; Carpenter and Williams 1995). Notably, Carpenter and Williams manipulated seven different probabilities between left and right target locations and found that saccade latencies can be plotted as a linear function of the continuous (from high to low) probabilities: highest probability is matched with shortest saccade latency and gradually steps down to lower probabilities with slightly longer latencies, until unfacilitated baseline performance. Recent studies have also shown that sensitivity to external probabilities, whether in a spatial (Chao et al 2011; Liu et al 2010, 2011) or temporal (trial-type probability—Chiau et al 2011; Juan et al 2008) sense, can even be robust enough to minimise the RT difference between pro- and anti-saccades. In these studies, however, manipulation of target location probability is often noticed by the participants because target location is the centre of attention in most tasks. Thus, one cannot tease apart the explicit use of strategies and implicit learning from these data. Therefore, whether or not the effect of continuous probabilities can be observed in implicit learning is still unclear. The present study combines the manipulation of a series of continuous probabilities with a contextual-cuing paradigm to investigate whether uneven probabilities of the context can also unevenly facilitate search efficiency such that the search benefit mimics the different probabilities of the visual context.

2 Methods

2.1 *Participants*

Fifteen right-handed participants (nine male, six female; aged between 20 and 23 years, mean age = 21.67 years) took part in the experiment for monetary payments. All had normal or corrected-to-normal vision. All participants gave informed written consent prior to the experiment.

2.2 *Material and procedure*

Participants sat 57 cm away from a 19-inch CRT display in a dimly lit room. They were instructed to find the target, which looked like a rotated T pointing either to the left or right, among L-shaped distractors that could appear in any orientation (figure 1). Participants responded with their right index and middle fingers on a response box, indicating left- and right-pointing targets, respectively.

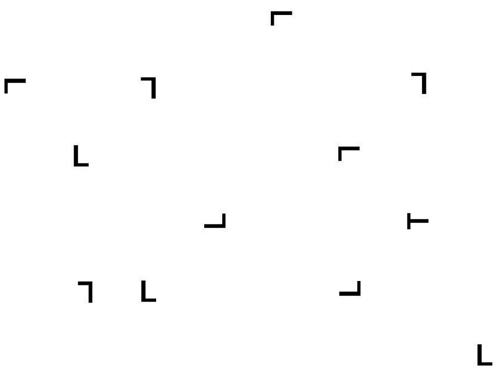

Figure 1. Sample display of a typical visual-search task. Participants were instructed look for a rotated T among eleven L-shaped distractors and report target orientation (pointing left or right). The configuration of surrounding distractors would repeat 1×, 2×, or 3× in the same block (cuing condition) or be randomly positioned (control condition).

All targets and distractors were presented in black on white backgrounds. The display was 1024 pixels wide and 768 pixels tall. All stimuli extended 40 pixels in height and width, and were presented in the centre 800 × 560 pixel area of the display. The display was evenly divided into four quadrants. Each quadrant, therefore, contained 10 × 7 possible locations for target and distractors. Target locations were counterbalanced and appeared equally frequently in all quadrants. Target locations in control trials (*new* condition, no repetition of context) matched those from trials with repeating context (*old* condition). Thus, strategically remembering target locations would help both *old* and *new* trials equally. Distractor layouts of *new* trials did not repeat. Finally, target identity was counterbalanced between *old* and *new* trials so that distractor configurations cued only target locations, but not their identity.

All participants completed 10 practice trials prior to the formal sessions of the experiment. In the experiment, each trial began with a 500 ms fixation cross, followed by a search array that contained one target and 11 distractors. The search array stayed on screen until a response was recorded. Each trial was then followed by a 750 ms inter-trial interval. At the end of the formal sessions, each participant was presented with a post-experiment questionnaire. The participants were asked whether they had noticed that certain trials were repeated throughout the experiment. If the answer was yes, they were asked whether they had explicitly attempted to memorise the distractor configurations. All participants were then given 24 trials of explicit recognition test. Half of the trials contained *old* configurations and the remaining half was a new set of *new* trials that had not appeared previously in the formal sessions.

2.3 *Design*

The experiment consisted of 25 blocks. Each block contained 28 *new* trials and 28 *old* trials. The 28 *old* trials can be broken down into 16 unique target–distractor configurations: 4 of which repeated three times (3×), 4 repeated twice (2×), and 8 that appeared once (1×). Target locations of these configurations were all evenly distributed across the four quadrants such that each quadrant contained a target from one 3× configuration, one 2× configuration, and two 1× configurations, for both *old* and *new* trials. Although the 1× trials were not repeated within blocks, they should still be considered as repeating trials since they appeared once in every block. This is analogous to the original design of *old* trials in other contextual-cuing studies (Chun and Jiang 1998). Again, note that the *new* trials only repeated target locations and their associated probabilities (3×, 2×, and 1×) of the *old* trials, but not the context.

3 Results

Participants' hit rate on the recognition test was 45.6%, which was not significantly different from their false-alarm rate (37.8%) ($t = 1.538$, $p = 0.235$). Of the fifteen participants, four claimed to have noticed trial repetitions. None of them indicated explicit attempts to memorise the distractor configurations. These four participants' performance in d' was not better than that of the unaware participants ($t = 0.16$, $p = 0.875$). This finding is similar to those reported by others, suggesting that the learning process behind this phenomenon is indeed implicit and not subject to conscious recognition.

As in most contextual-cuing studies, our data from 25 blocks were grouped into 5 epochs to increase statistical power. These data were then submitted to a $5 \times 2 \times 3$ ANOVA with independent variables of epoch (1 to 5), context (*old* and *new*), and probability (3×, 2×, and 1×). The analysis revealed a significant main effect for all three independent variables (epoch: $F_{4,56} = 82.35$, $p < 0.001$; context: $F_{1,14} = 49.89$, $p < 0.001$; probability: $F_{2,28} = 92.35$, $p < 0.001$), as well as all the interactions between them (epoch × context: $F_{4,56} = 3.82$, $p < 0.01$; epoch × probability: $F_{8,112} = 6.05$, $p < 0.001$; context × probability: $F_{2,28} = 13.85$, $p < 0.001$; epoch × context × probability: $F_{8,112} = 4.17$ $p < 0.001$).

We examined the effect of contextual cuing separately by conducting a 2-way ANOVA (epoch × context) under each probability (1×, 2×, and 3×). These results are shown in figures 2 and 3. Under probability 1×, the effect of epoch was a significant factor ($F_{4,56} = 77.29$, $p < 0.001$) but context repetition (*old* trials) was not ($F_{1,14} = 0.01$, $p > 0.05$). This can be explained by the significant interaction between epoch and context ($F_{4,56} = 9.06$, $p < 0.001$), which was driven by the late emergence of contextual cuing (between 2nd and 3rd epoch—figure 2, left graph). This is consistent with

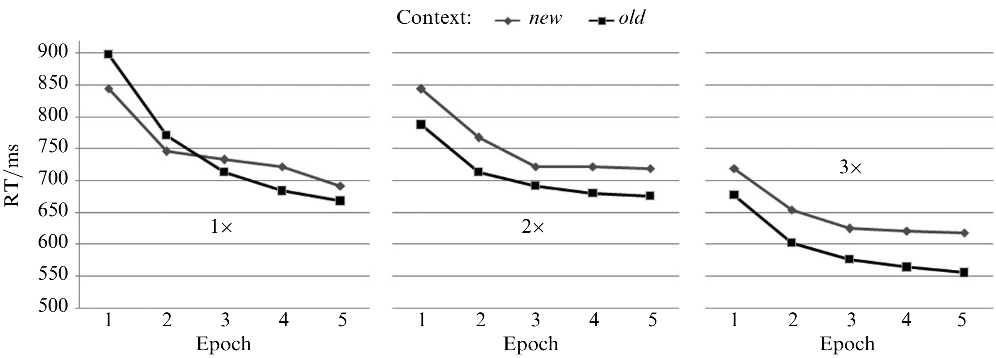

Figure 2. Contextual-cuing effect under different probabilities. An effect of epoch is clearly present, showing improvement over time. Moreover, RTs from the old (repeating context) condition are always faster than those from the new condition (no context repetition). These trends replicate the classic contextual-cuing effect. Looking at the effects of probability separately, probability 1× shows late learning effect (superseding control RTs halfway between 2nd and 3rd epoch), which is consistent with other contextual-cuing studies (Chun and Turk-Browne 2008, page 215). Other probabilities yield early contextual facilitation.

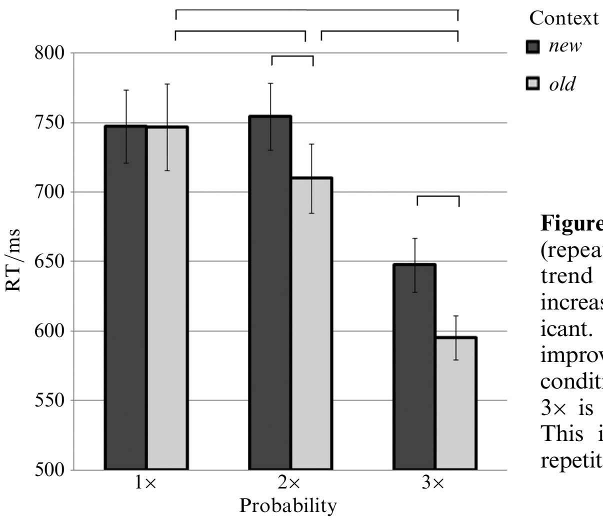

Figure 3. Effect of probability. Under the old (repeating context) condition a decreasing trend in RT is clearly visible as probability increases. All pairwise comparisons are significant. This downward trend shows a gradual improvement from contextual cuing. In the new condition (no context repetition), however, only 3× is significantly different from 1× and 2×. This is likely a result from target location repetitions. Error bars represent ±1 SEM.

previous work on contextual cuing (Chun and Jiang 2003; Chun and Turk-Browne 2008, page 215), as the visual system requires certain amount of exposures before reliable statistical information can be confirmed. Under probabilities 2× and 3×, the effect of contextual cuing was robust. Both epoch and context were highly significant (2× epoch: $F_{4,56} = 26.92$, $p < 0.001$; 2× context: $F_{1,14} = 67.06$, $p < 0.001$; 3× epoch: $F_{4,56} = 50.07$, $p < 0.001$; 3× context: $F_{1,14} = 41.02$, $p < 0.001$), with no interaction (2×: $F_{4,56} = 0.83$, $p > 0.05$; 3×: $F_{4,56} = 0.58$, $p > 0.05$). Together, these results indicate that participants had eventually learned these contexts implicitly to facilitate visual search despite the differences in their probabilities.

To further elucidate the effect of differential probabilities, we collapsed RTs from all five epochs and looked at these averaged RTs across all three probabilities, as shown in figure 3. Two-way ANOVA (context × probability) revealed a significant main effect of context ($F_{1,14} = 49.89$, $p < 0.001$) and probability ($F_{2,28} = 92.35$, $p < 0.001$), as well as an interaction between them ($F_{2,28} = 13.84$, $p < 0.001$). Simple main-effect ANOVAs showed that probability was a significant factor in both *old* ($F_{2,28} = 65.88$, $p < 0.001$) and *new* ($F_{2,28} = 100.98$, $p < 0.001$) displays. Fisher's LSD a-posteriori tests were then conducted to probe the RT differences between the three probabilities. In the *old* condition, participants performed best under probability 3× (595.13 ms), mediocre at 2× (709.97 ms), and worst at 1× (746.82 ms). All three figures were significantly different in Fisher's LSD analysis (1× versus 2×: $p < 0.01$; 1× versus 3×: $p < 0.001$; 2× versus 3×: $p < 0.001$). This is the critical finding of the present study as it demonstrates a clear graded continuum in implicit-memory strength. In the *new* condition, participants also performed best under probability 3× (647.55 ms) (3× versus 1×: $p < 0.001$; 3× versus 2×: $p < 0.001$). However, their performances under probability 1× (747.51 ms) and 2× (754.69 ms) was equally poor and not significantly different from each other ($p = 0.36$). Therefore, where repeated contexts produced a downward linear trend when probability increased, this trend was less apparent when contexts did not repeat.

4 Discussion

In the present study, we manipulated the rate of exposure of different visual contexts. This was done with the intention to manipulate the degrees of learning, or the strengths of associations, in order to investigate the nature of implicit learning. Specifically, is implicit memory also organised on a continuum of memory strength? And if so, can these different levels of implicit information aid one's performance accordingly?

Our findings showed that this was indeed the case. We observed a linear decrement of RTs as probability increased. This was not the case when contexts did not repeat. Therefore, the degrees of contextual cuing behaved as a function of their memory strengths despite a lack of conscious effort to retrieve and use this information. This suggests that the general statistical regularities of visual contexts are not only encoded, but are encoded in a way that incorporates the specific likelihood with which these regularities are closely associated.

Although the effect of contextual cuing is argued by most as implicit (participants cannot recognise repeated context beyond chance level), it is important to note that it remains possible that the post-experiment recognition test was not sensitive enough to uncover the explicit memory traces. The post-experiment recognition test also offers no temporal resolution, and therefore is not able to detect explicit memory traces at the time of the search trials that can be lost by the end of the experiment. Therefore, although participants cannot recognise repeated contexts better than chance level, the extent of implicit and explicit memory processes in contextual cuing remains to be tested by future studies. It is also important to note that studies manipulating probabilities of target locations often risk the confounding effect of trial-to-trial facilitation (Walthew and Gilchrist 2006). In our case, trials with probability of 3× were more likely to appear consecutively by chance, thus benefitting from a priming effect. We also observed this phenomenon since participants' RT improved rapidly under probability 3× even when contexts did not repeat. However, since the target locations from our *new* trials were completely identical to those in the *old* trials, the observed 'gaps' between RTs from the *old* and *new* conditions under all probabilities (figure 2) can only be attributed to the facilitation of repeated contexts.

Indeed, these 'gaps' are perhaps the most revealing findings in our data. Upon a careful look at figure 2, one may find that, towards the end of the experiment (epoch 5), RTs from the 2× condition did not seem to be any faster than those from the 1× condition. On the surface, this seems to go against the idea of a graded manifestation of implicit learning. However, even when the contextual-cuing effect from the 1× condition stabilised (starting from epoch 3), the 'gap' between the *old* and *new* conditions in the 2× condition was wider than that from the 1× condition and narrower than the 3× condition. Therefore, the effect of contextual facilitation indeed followed a graded manner even when the 1× condition started showing stabilised contextual-cuing effect. So why was the gap wider but not faster in the 2× condition when compared to the 1× condition? This can be explained by the difference in task difficulty across conditions, which can include a number of factors such as target positions, number of distractors surrounding the target, and their distances from the target. For example, if the target was in an easier position to spot on more trials in the 1× condition than the 2× condition, this potentially explains why the RTs from 2× never really improved over those from 1×.[1] The lack of practice effect (flat slope from epoch 3 to 5) in the 2× condition perhaps supports this rationale. Therefore, comparing the final-epoch RT between probabilities is misleading because it assumes equivalent difficulty across all conditions. We think the gaps between the *old* and *new* conditions, starting from epoch 3 where the contextual-cuing effect of the 1× condition became stable, may be more telling of the graded nature of implicit learning.

[1] We conducted a subsequent study that incorporated four versions of the original task with four new participants. Among the four versions, all target – distractor configurations and their respective probabilities were counterbalanced, so that the difference between difficulties is no longer an issue. Although the sample size was small, the same 'gap' effect was still present, where 1× received the least amount of facilitation, then 2× and 3×. In addition, the 2× condition also enjoyed a faster RT than the 1× condition, confirming our discussion here.

5 Conclusion

There are clear benefits to implicitly remembering contextual information. On one hand, explicitly remembering each individual context can be computationally costly; yet learning these predictive patterns can save more time and effort in the long run. Indeed, previous research has demonstrated a remarkable durability of such implicit associations, suggesting that such information is not simply stored for short-term facilitations (Chun and Jiang 2003). Hence, implicit learning and storage of contextual information can be viewed as an optimal compromise adopted by the visual system to serve long-term interest in an efficient way. These advantages have been well-documented, including directing eye movements and attention to relevant locations (Peterson and Kramer 2001a) and ignoring other salient but non-predictive events such as abrupt onsets (Peterson and Kramer 2001b). The present study extends these findings and demonstrates that the visual system can be sensitive to the global statistical properties of each event. This sensitivity to the relative likelihood of each individual context gives more statistical power to the visual system for making optimal decisions that help us navigate through a variety of different environments. In addition, the present study also highlights the importance of the temporal aspect of implicit learning, as the total number of exposures cannot fully account for our findings here. Future studies should further test the robustness of such probabilistic learning in implicit-learning paradigms that cue target location or identity with relational (Fiser and Aslin 2001) or temporal (Fiser and Aslin 2002) regularities.

Acknowledgments. We thank Bruce Bridgeman for a helpful discussion, and two anonymous reviewers for their comments which improved this paper. We also thank Wen-Shin Sung and Yu-Ching Tsai for their help in data collection. This work was sponsored by the National Science Council, Taiwan, and the Academia Sinica, Taiwan. TYH, OJLT, DLH, and CHJ were supported by the National Science Council, Taiwan (99-2410-H-008-022-MY3, 99-2911-I-008-025, 97-2511-S-008-005-MY3, 98-2410-H-008-010-MY3, 98-2517-S-004-001-MY3, and 97-2511-S-008-008-MY5).

References

Carpenter R H, 2004 "Contrast probability and saccadic latency: Evidence for independence of detection and decision" *Current Biology* **14** 1576 – 1580

Carpenter R H, Williams M L, 1995 "Neural computation of log likelihood in control of saccadic eye movements" *Nature* **377** 59 – 62

Chao C M, Tseng P, Hsu T Y, Su J H, Tzeng O J L, Hung D L, Muggleton N G, Juan C H, 2011 "Predictability of saccadic behaviors is modified by transcranial magnetic stimulation over human posterior parietal cortex" *Human Brain Mapping* doi:10.1002/hbm.21162

Chiau H Y, Tseng P, Su J H, Tzeng O J L, Hung D L, Muggleton N G, Juan C H, 2011 "Trial type probability modulates the cost of antisaccades" *Journal of Neurophysiology* **106** 515 – 526

Chun M M, Jiang Y, 1998 "Contextual cueing: implicit learning and memory of visual context guides spatial attention" *Cognitive Psychology* **36** 28 – 71

Chun M M, Jiang Y, 2003 "Implicit long-term spatial contextual memory" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **29** 224 – 234

Chun M M, Turk-Browne N B, 2008 "Associative learning mechanisms in vision", in *Visual Memory* Eds S J Luck, A Hollingworth (New York: Oxford University Press) pp 209 – 245

Fiser J, Aslin R N, 2001 "Unsupervised statistical learning of higher-order spatial structures from visual scenes" *Psychological Science* **126** 499 – 504

Fiser J, Aslin R N, 2002 "Statistical learning of higher-order temporal structure from visual shape sequences" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **283** 458 – 467

Geng J J, Behrmann M, 2002 "Probability cuing of target location facilitates visual search implicitly in normal participants and patients with hemispatial neglect" *Psychological Science* **13** 520 – 525

Geng J J, Behrmann M, 2005 "Spatial probability as an attentional cue in visual search" *Perception & Psychophysics* **67** 1252 – 1268

Jiang Y, Wagner L C, 2004 "What is learned in spatial contextual cuing—configuration or individual locations?" *Perception & Psychophysics* **66** 454 – 463

Juan C H, Muggleton N G, Tzeng O J, Hung D L, Cowey A, Walsh V, 2008 "Segregation of visual selection and saccades in human frontal eye fields" *Cerebral Cortex* **18** 2410 – 2415

Kunar M A, Flusberg S J, Wolfe J M, 2006 "Contextual cuing by global features" *Perception & Psychophysics* **68** 1204 – 1216

Liu C L, Chiau H Y, Tseng P, Hung D L, Tzeng O J, Muggleton N G, Juan C H, 2010 "The anti-saccade cost is modulated by contextual experience of location probability" *Journal of Neurophysiology* **103** 1438 – 1447

Liu C L, Tseng P, Chiau H Y, Liang W K, Hung D L, Tzeng O J L, Muggleton N G, Juan C H, 2011 "The location probability effects of saccade reaction time are modulated in the frontal eye fields but not in the supplementary eye field" *Cerebral Cortex* **21** 1416 – 1425

Olson I R, Chun M M, 2002 "Perceptual constrains on implicit learning of spatial context" *Visual Cognition* **9** 273 – 302

Peterson M S, Kramer A F, 2001a "Attentional guidance of the eyes by contextual information and abrupt onsets" *Perception & Psychophysics* **63** 1239 – 1249

Peterson M S, Kramer A F, 2001b "Contextual cueing reduces interference from task-irrelevant onset distractors" *Visual Cognition* **8** 843 – 859

Shaw M L, Shaw P, 1977 "Optimal allocation of cognitive resources to spatial locations" *Journal of Experimental Psychology: Human Perception and Performance* **3** 201 – 211

Walthew C, Gilchrist I D, 2006 "Target location probability effects in visual search: an effect of sequential dependencies" *Journal of Experimental Psychology: Human Perception and Performance* **32** 1294 – 1301

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 40 2011

www.perceptionweb.com