

Inference-driven Mechanisms of Attentional Orienting

Paolo Cherubini, Michele Burigo, Emanuela Bricolo

Dipartimento di Psicologia, Università di Milano-Bicocca,

1, p.zza dell'Ateneo Nuovo, 20121 Milano (ITALY)

e-mail of first author: paolo.cherubini@unimib.it

Abstract

In this paper we present some empirical data in support of a new view of attentional orienting, according to which (a) some basic mechanisms of attentional deployment (i.e. its high efficiency in dealing with expected and unexpected inputs) meet the requirements of the inferential system, and have possibly evolved to support its functioning; and (b) these orienting mechanisms function in very similar ways in different domains, i.e. in perceptual tasks and in symbolic tasks. After sketching the basics of the model and of its specific predictions, we report the results of 3 behavioral experiments where participants tracked visual trajectories (Experiments 1 and 3) or arithmetic series (Experiments 2 and 3), responding to the onset of a target event (e.g., to a specific number) and to the repetition of an event (e.g., a number appearing twice consecutively). Target events could be anticipated when they were embedded in regular series/trajectories; they could be anticipated, with the anticipation later disconfirmed, when a regular series/trajectory was abruptly interrupted before the target event occurred; and could not be anticipated when the series/trajectory was random. Repeated events could not be anticipated. Results show a very similar pattern of allocation in tracking visual trajectories and arithmetic series: attention is focused on anticipated events, it is defocused and redistributed when an anticipation is not confirmed by ensuing events, while performance decreases when dealing with random series/trajectory, i.e. in absence of anticipations. The behavioral results were later supported by an electrophysiological investigation using Event Related Potentials. In our view, this pattern of allocation of attention is due to the fact that confirmed and disconfirmed anticipations are crucial events for knowledge revision, i.e. the fine tuning of the inferential system to the environment; attentional mechanisms have developed so as to enhance detection of these events, possibly at all levels of inferential processing.

The cognitive system is a tool to build and maintain representations isomorphic to the environment (Newell, 1990). Within it, inferential processes expand representations of the environment beyond direct sensorial information. Inferential processes are almost ubiquitous, being involved both in perceptual tasks and in symbolic tasks. Inferences in different domains can have different processing times, levels of consciousness, and precision (Berry, 1997; Holyoak & Spellman, 1993; Rips, 2001; Seger, 1994). However, at a computational level of analysis (that is, con-

sidering what inferential processes do rather than how they do it; Marr, 1982), inferential processes in all domains perform three main functions (see also the “perceptual cycle” by Neisser, 1976):

1. They gather conjectural knowledge about predictive regularities in the environment (*inductive function*);
2. They use the knowledge in (1) to anticipate states of affairs that are beyond the sensorial horizon (*deductive function*);
3. They compare the anticipations in (2) with ensuing states of affairs, in order to strengthen the knowledge that generated them if anticipations are confirmed, or to weaken or abandon the knowledge that generated them if anticipations are not confirmed (*knowledge revision function*).

When inductive processes are unable to sort out predictive regularities in a local environment, the resulting perception is that of randomness: psychologically, the judgment of randomness results from the repeated failure of attempts to find regularities (Bar-Hillel & Wagenaar, 1991; Diener & Thompson, 1985; Falk & Konold, 1997). Random environments are those where no deductive anticipations of ensuing states are possible.

Knowledge revision, function (3) in the schema above, is of paramount importance in order to preserve the isomorphism between the environment and its mental representations. Without it the cognitive system would soon cease to be useful in navigating the environment, because its anticipations would hopelessly diverge from reality. The two clues that trigger knowledge revision are confirmed and disconfirmed anticipations, namely expected and unexpected events, as opposed to random events, that is events that occur in absence of any anticipation (i.e., events that do not conform to an expectation, but neither do they contrast with existing expectations). Confirmed and disconfirmed expectations are a sort of litmus test to check whether our knowledge is fine-tuned to the environment. Accordingly, attention, conceived as the set of processes that select potentially relevant information in the environment and enhance its processing, should be biased toward expected and unexpected events, because of their crucial importance as a test of the soundness of our knowledge

about the environment. The attentional system should be at a loss, not “knowing” what to select, when confronted with random environments. In other words, the attentional system should have evolved so as to be oriented by inferences, spontaneously focusing on anticipated events and rapidly detecting their confirmations and disconfirmations, so as to allow keeping an up-to-date knowledge base. This general pattern of attentional orienting should be detectable in perceptual tasks as well as in symbolic tasks.

Previous research has documented an apparently contradicting finding: on one hand, attention is biased in favor of new, unexpected events, as shown by *novel popout* effects (e.g., Hawley, Johnston, & Farnham, 1994; Johnston & Schwarting, 1996, 1997), by the automatic orienting toward the *abrupt onsets* of unexpected objects (Hillstrom & Yantis, 1994; Rauschenberger & Yantis, 2001; Remington, J.C. Johnston, & Yantis, 1992), and by the existence of dedicated mechanisms, like *inhibition of return* (Posner & Cohen, 1984; Posner, Snyder, & Davidson, 1980) that facilitate the exploration of new locations (Klein, 1988; Klein & MacInnes, 1999; Posner, Rafal, Choate, & Vaughan, 1985; Pratt, O'Donnell, & Morgan, 2000; Pratt & McAuliffe, 2002). On the other hand, there is evidence that the perceptual system is advantaged in perceiving and localizing items expected in a given context (e.g., Biederman, Mezzanotte, & Rabinowitz, 1982; Jacoby & Dallas, 1981), and sometimes it has great difficulties in perceiving change (e.g., Rensink, 2002). This apparently contradicting results suggest that the “...the mind appears to be biased simultaneously toward both expected and unexpected inputs” (Johnston & Hawley, 1994, p. 56). However, this puzzling conclusion can be accounted for by the conjecture that the attentional processes are servo-mechanisms aimed at delivering pieces of information that are potentially useful for knowledge revision: attention is not affected by events “per se”, but by the relative bearing of those events with respect to cognitive expectations. The very same event can sometimes attract attention, and sometimes not, according to whether they are relevant to an existing anticipation (either by confirming or disconfirming it), or not. When the event confirm or contradict a previous expectation, it is potentially useful for knowledge revision, and it will affect the orienting of attention; on the contrary, when it is neutral toward any existing expectation, it will not have any effect on the orienting of attention. For example, given the list “2 – 4 – 6 – 8 – N”, if an N = 10 is presented thereafter it should attract attention, for the reason that it gives support to a previously conjectured regularity in the series. Even an N≠10, i.e. 12, should attract attention, for the opposite reason that it shows that the alleged regularity in the series was inconsistent. However, if the series were “12 – 7 – 8 – 31 – 5 – N”, neither N=10 nor N=12 should affect attention in any meaningful way: no obvious anticipation were made concerning the magnitude of the ensuing

number, and accordingly the presented number neither confirm nor disconfirm an existing anticipation.¹

However, a further question arises: do the two biases for expected and unexpected stimuli work in the same way, or are they different? That is, in the “2 – 4 – 6 – 8 – N” example, do the N=10 and the N=12 event have the same effect on the orienting of attention, or a different one? In our view, a confirmed expectation (like N=10) simply serves as a reassurance that the current knowledge base, in that particular domain, is correct and does not need revision; accordingly, no further gathering of different information is needed. On the other hand, an unfulfilled expectation, like when N=12, signals that the current knowledge base is not satisfactory for the domain of reference, and should be revised or expanded: accordingly, even though it should be initially hard to detect (because the system is focused on the anticipation), once detected attention should be rapidly defocused in order to explore the surrounding environment for gathering new information, in an attempt to draw some conjecture about why the prediction was unfulfilled (i.e., seeking new, different regularities in the environment).

In a recent study (Cherubini, Burigo, & Bricolo, 2005), we tested the following specific predictions derived from the general hypotheses above: (1) attention focuses on anticipated states of affairs, so as to enhance processing of a correctly anticipated event; (2) disconfirmed anticipations trigger defocusing and redistribution of attentional resources in order to gather new information about the environment; (3) in absence of anticipations (i.e., in a random environment), attention should lack proper guidance, resulting in decreased performance; (4) the above predictions 1-3 are domain-independent: inference-driven attention should operate in similar ways in perceptual and in symbolic tasks; and (5) attention-driving inferences do not depend exclusively on the detection of statistically predictive associations between environmental clues and target events, but rather on the inner mechanisms of the inferential system (i.e., detection, abstraction and generalization of structural regularities; see Pena, Bonatti, Nespor, & Mehler, 2002, for implicit processes of structure abstraction, and Cherubini, Castelveccchio & Cherubini, 2005, for explicit processes). Experiments 1 and 2 concerned predictions 1-3 and 5 above. The comparison between them concerned prediction 4, since the task was perceptual in Experiment 1 (tracking a visual trajectory), but it was symbolic in Experiment 2 (tracking an arithmetic series).

Many previous studies of visual attention have used synchronic tasks: for example, classical search tasks involving

¹ Of course, the “random” series allow the anticipation that N is a number, whichever it is. If instead a letter is presented, it should violate that anticipation, and affect attention. However, we did not gather empirical data concerning this sort of higher-level anticipations.

feature singletons (for a review, cf. Yantis, 1996) usually display an array of similar elements with one element (or a few) differing in one dimension. In those studies the feature singleton is “unexpected”, because it contrasts with an expectation grounded on the coherence of the background elements. However, elements in support of the expectation and elements that disconfirm it are simultaneously available, an unusual occurrence in most inferential processes. Since most inferences are diachronic (i.e., individuals predict an event on the ground of something else that occurred, or was perceived, before it), this sort of task is ill suited to study the role of inferences in the orienting of attention. In many other studies, namely those using cues, an element appears on a display for a brief period of time before a target probe. If the cue is statistically predictive of the target, participants are told so. This sort of diachronic task is more suitable for studying the role of inferences in attention. However, it is extremely impoverished: instead of perceiving and extrapolating regularities assumed to be predictive, the participants are a priori told which these regularities are, and their statistical validity: the inductive inferential function is completely omitted, differently from what occurs in real-world cognition.

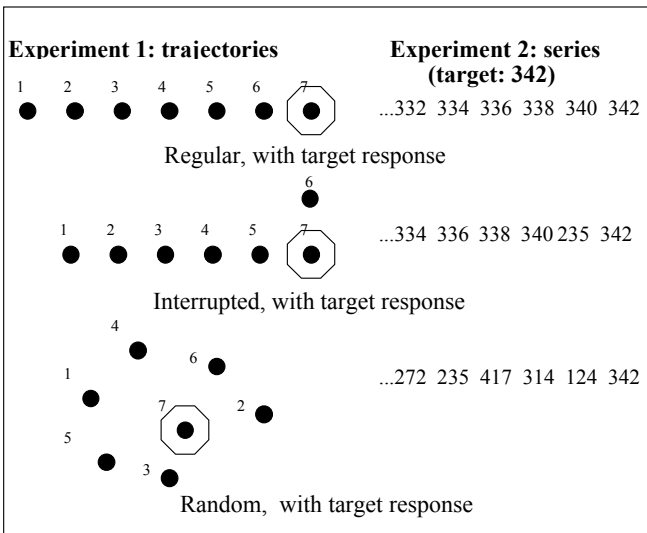


Figure 1. Simplified examples of regular, interrupted, and random series, in Experiments 1 and 2. All the examples shown require a target response, but in the real experiments each series was equally associated with target responses, responses to repeated dots or numbers, or no responses. In Experiment 2 all the numbers appeared at the center of the screen. The small numbers over the dots were not present in the real task: they are displayed here to show the sequential order of presentation of the dots.

Therefore we devised a new sort of tasks, which required diachronic inferences based on regularities that the participants had to perceive and extrapolate by themselves from a

continuous flow of events (i.e., without clearly marked intervals between different experimental trials).

In Experiment 1 The task required the participants to follow a small round dot intermittently flashing on the screen, and to respond to two events, one predictable (in some conditions) on the ground of regularities in the previous locations of the dot, and one unpredictable (in all conditions). The dot could be arranged to appear in a) locations forming an uninterrupted regular trajectory (“regular series”); b) locations forming a previously regular trajectory, later interrupted by an unexpected dot (“interrupted series”); c) random locations (“random series”. The participants must strike a key when a dot appeared within a target outlined in the center of the screen (“target responses”), and a different key when two consequent dots appeared in the same location (“repeated-dot response”). In regular series, the target responses could be correctly anticipated as the prosecution of the trajectory. In the interrupted series, the dots could be correctly anticipated up to the one preceding the target position: that one appeared in a stray location, abruptly disconfirming the participants’ expectations. If a target event followed, it was after an event that disconfirmed an anticipation. In the random series, the target event could never be anticipated. Likewise, the repeated-dot event could not be anticipated in any of the three conditions. In Experiment 2 the task was analog to that in Experiment 1, but arithmetic series were presented instead of visual trajectories. All the numbers in a series were presented at the center of a computer screen. The regular series were uninterrupted sequences of numbers showing some very easy regularity; the interrupted series were like the regular series, but one of the numbers violated the regularity, abruptly disconfirming any anticipation concerning them. Random series were series of pseudo-random numbers. The events requiring a target response was a specific number (target number). When the same number was repeated twice consequently, participants had to produce a repeated-number response. Target numbers could be correctly anticipated in regular series; they followed a disconfirmed prediction in interrupted series; they could not be anticipated and did appeared in absence of any specific prediction in random series. The occurrence of repeated numbers could never be anticipated.

		Series / trajectory		
		regular	random	interrupted
response required	target	Correctly anticipated	No anticipations possible	Following an unfulfilled anticipation
	repeated	Contrasting with an anticipation	No anticipations possible	Following an unfulfilled anticipation

Table 1. The six experimental conditions

Each one of the six resulting experimental conditions (see Table 1) comprised 32 trials (192 trials overall); a further 96 filling trials (32 for each type of series) did not include any response requiring event. Accordingly, there was no statistical association between the type of series/trajectory and the required response: for example, the regular series/trajectory included one third of the times a target event, another third a repeated event, and the last third no response events at all. Accordingly, the predictions concerning the target events in regular and interrupted series were supported by the extrapolation of a perceived regularity, but were not statistically sound. Examples of series/trajectories including target events are reported in Figure 1. Participants were 12 (Experiment 1) and 18 (Experiment 2) students from the universities of Milano and Plymouth. Latencies and correctness of the responses were registered (the latter will not be discussed here). The results are synthesized in Table 2 and in Figure 2.

		Series / trajectory		
		regular	random	interrupted
Trajectories	target	389	536	448
	repeated	516	528	451
Arithmetic series	target	550	681	665
	repeated	726	683	652

Table 2. Response latencies in the 6 experimental conditions, in ms.

Statistical analyses showed that all of the experimental predictions were fulfilled, as follows:

1. *Processing of anticipated events is advantaged over processing of unexpected events.* This is shown by the fact that target responses in regular series (which were very easily anticipated as the continuation of the trajectory) were reliably faster than responses to repeated events in the same condition (which could not be anticipated).
2. *Unfulfilled predictions trigger the redistribution of attentional resources.* In the interrupted series, where a displaced dot/number abruptly disconfirmed the anticipations of an incoming target event, participants were equally fast in responding to the target events and to the repeated events. With respect to the regular series, target responses slowed down, whereas repeated-event responses grew faster. These findings suggest that participants defocused from the wrongly anticipated target response and redistributed attention to both responses, consistently with the predictions. We termed this effect the “surprise effect”: the since she is actively expecting the occurrence of an event, the participant is taken off-guard by the occurrence of a different, unexpected event, and accordingly is slow in processing it (as shown by the finding 1). However, the disconfirmed anticipation signals the need to upgrade one’s own knowledge: as a consequence, attention is redistributed,

and immediately after the surprise the individual is capable to answer with equal efficiency to all response events. Whilst some of the other results can be accounted for by different theories of attention (for details, see Cherubini, Burigo, et al., 2005), up to now the surprise effect is predicted only by our current conjecture that what is important, for attentional orienting, is the relative bearing of specific events with respect to the cognitively-built anticipations of the environment.

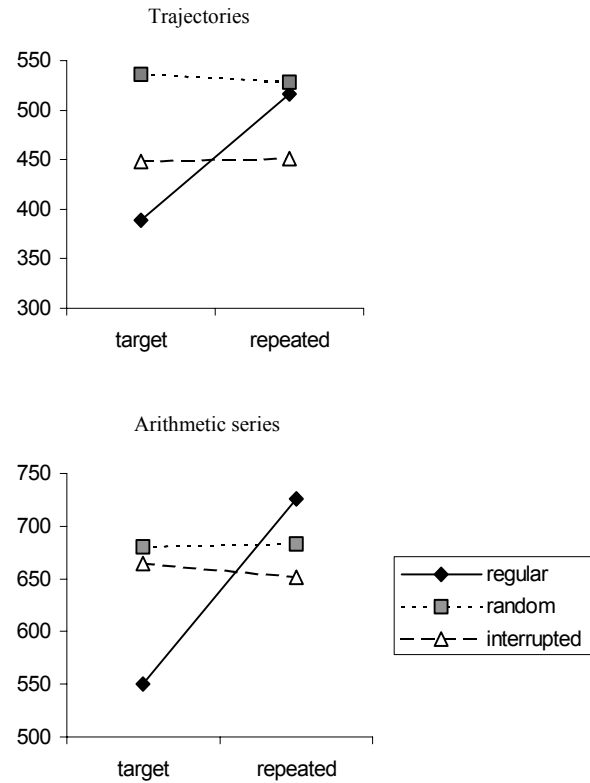


Figure 2. Response latencies in the 6 experimental conditions in Experiment 1 (trajectories) and 2 (arithmetic series)

3. *Performance decreases in random environments.* In the random conditions, participants could not perceive regularities that allowed anticipating any response event. As a result, responses to both events were slow with respect to the other conditions, except for repeated-event responses in the regular condition. These findings are consistent with the hypothesis that attentional mechanisms are fine-tuned to the requirements of the inferential system, and do not work efficiently when the inferential processes are “switched off” by a random environment.
4. *Inference-driven orienting of attention is domain-independent.* The only reliable difference between the patterns of latencies observed in the two experiments concerned the random conditions, whose responses were relatively faster in the arithmetic series task than in the visual

trajectory task. However, this unpredicted finding does not affect the main finding: the interaction between the type of series and the type of response-event occurs in both the perceptual and the symbolic task, with very similar patterns, whose differences are not statistically reliable. Even though absolute response latencies were different, and the absolute values of differences between conditions were different, the directions of all significant differences between conditions were the same. In both experiments attention was focused on anticipations, and was defocused and redistributed when an anticipation was abruptly disconfirmed; in both experiments performance decreased in random conditions, except with respect to repeated-event responses in regular conditions. In our view, the results suggest that inference-driven attentional orienting involves similar mechanisms disregarding the domain upon which the inferential system is operating.

5. The effect of confirmed and disconfirmed anticipations over attention is not limited to statistically predictive anticipations. There were no statistically predictive associations between the type of series/trajectories and the responses that were to be given: i.e., regular series were followed in an equal number of trials by in-target responses, repeated-dot responses, and no responses. Accordingly, anticipations affect the orienting of attention even when they are not statistically sound: in other words, attention is guided by inferences, disregarding whether those inferences are grounded on statistical regularities, or on any other type of regularity perceived by the cognitive system. From a broad perspective, this is a minor but theoretically important point: in fact, the human cognitive system is sometimes very good at detecting statistical regularities (e.g., McKenzie, 1994), but it is also prone to illusory correlations (e.g., Chapman, 1967; Fiedler, 2000), that is perceiving alleged regularities where there are none. Actually, this is one of the cognitive roots of important social problems, such as negative stereotyping of outgroup minorities (Hamilton, Dugan, & Trolor, 1985; Hamilton & Gifford, 1976). For example, if a person illusorily believes that a member of a minority group X is more likely than a member of a majority group Y to commit a crime, and wishes to avoid becoming a victim, she will probably orient attention so as to promptly detect any nearby member of X: in so doing, she would be orienting attention on the ground of an inferential expectation, but not one which is statistically sound.

The most important criticism of our interpretation of the previous results concerns the actual involvement of attention in them: that is, the same pattern of responses could be caused, rather than by the orienting/reorienting of attention, by the motor preparation of the anticipated response. Once that a target response has been anticipated, the finger that should produce it is pre-activated: the successive, sudden necessity to switch to a different response by a differ-

ent finger is hindered. This effect could cause the difference between target responses and repeated-event responses in the regular conditions (result 1 above). According to the same view, the disconfirmation of an expectation could cause the gradual redistribution of the pre-activation of the target response to both responses, with no need to conjecture that the effect is caused by the redistribution of attention. In order to deal with this alternative interpretation, a third experiment was run where participants were instructed to respond by pressing the same key with the same finger any time they saw a response-event, whether it was a target event, or a repeated event. Experiment 3 involved both a visual and a symbolic task. Whilst the symbolic task was almost exactly the same as in Experiment 2 (tracking arithmetic series), the visual task was somewhat different from Experiment 1: in fact, participants were shown with a display mimicking the face of a clock, with an arm moving on it. The trajectories traced by the arm were either regular (clockwise or counterclockwise), interrupted, or random. The target event was a specific hour (for example, 6 o'clock), whereas the repeated event occurred when the arm appeared twice consecutively in the same. By using this task, we could instruct the participants to keep their eyes fixed on the same spot (the center of the clock) for the whole experiment: accordingly, we could check whether the pattern obtained in Experiment 1 was dependent on covert movement of attention, or occurred only when overt eye movement were involved (as in Experiment 1). The results, displayed in Figure 3, showed a striking simi-

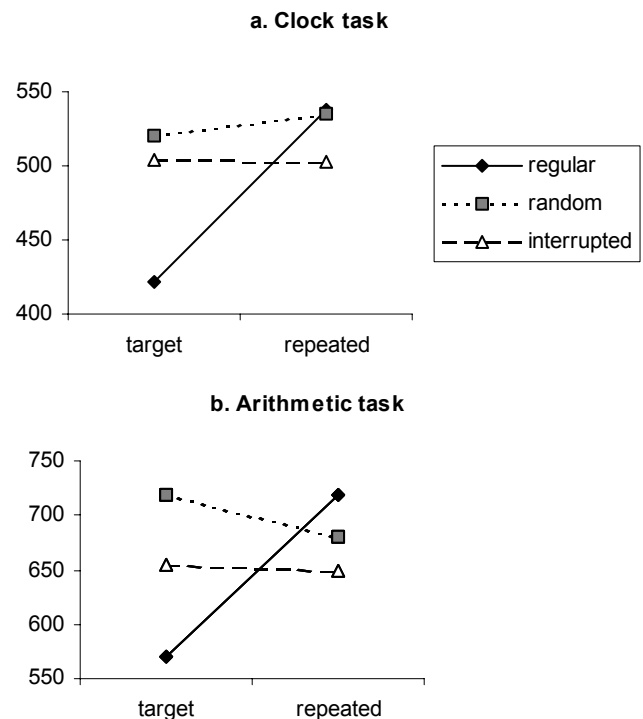


Figure 3. Response latencies in Experiment 3

larity to the results obtained in the Experiments 1 and 2. Of course, the observed similarities in the orienting of attention in visual and symbolic tasks are at a functional and behavioral level, and they do not necessarily imply similarities of the underlying neural substrate. However, Castelveccchio, Vallesi, Mapelli, and Cherubini (2004) recorded the event-related potentials (ERP) along the mid-sagittal line (in frontal [Fz], central [Cz] and posterior [Pz] locations), in correspondence to the response events and to the immediately preceding events (that is, the events that, in the interrupted series, abruptly disconfirmed the anticipation of the target event). The tasks and stimuli were exactly the same as in Experiment 3 (apart from a mild lengthening of the presentation times, that was necessary in order to record reliable ERPs). The trends of the response latencies replicated those observed in Experiment 1, 2 and 3. The potentials related to the events preceding the response events showed a statistically reliable peak of the P300 wave in the interrupted condition (that is, in the condition in which that event contradicted the anticipation of the target event). This pattern occurred both in the perceptual task and in the arithmetic task (Figure 4), and is consistent with previous research showing ample P300 waves

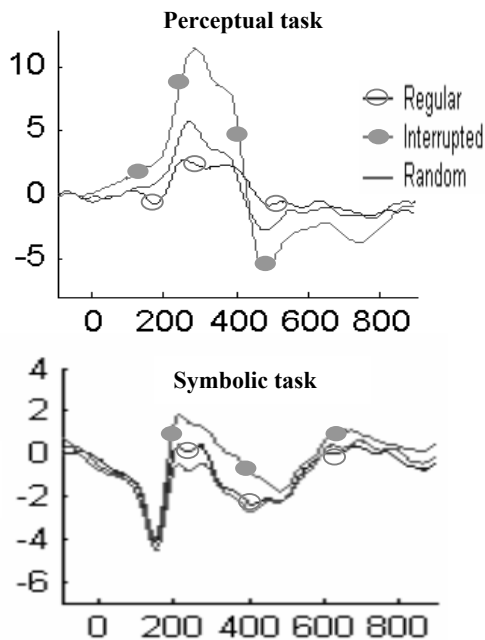


Figure 4. ERPs in the Cz mid-sagittal site, in correspondence with the event preceding the response event. Time (X-axis) is in ms, potentials (Y-axis) are in μV .

elicited by stimuli contrasting with previous expectations, in auditory, visual and numeric sequences (e.g., Lang & Kotchoubey, 2002; Johnson, 1988; Polich, 1985; Squires, Wickens, Squires, & Donchin, 1976). However, a similar P300 peak was also present in correspondence of the cor-

rectly anticipated target event in regular series/trajectories (Figure 5): in other words, the brain responded in a similar way to the confirmation and disconfirmation of a task-relevant expectation. Since the amplitude of the P300 varies proportionally to the attention paid to the stimulus (Sommer, Math, & Leuthold, 1990; Johnson, 1988), the similar brain response to confirmed and disconfirmed expectations is a clue consistent with our proposal that these events are important signals affecting the allocation of attention.

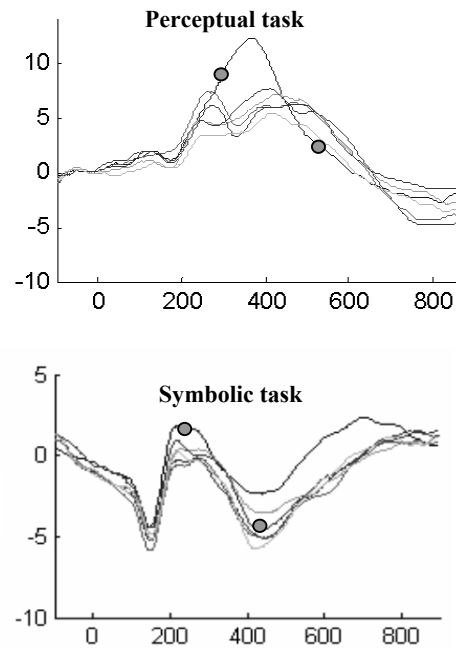


Figure 5. ERPs in the Cz mid-sagittal site, in correspondence with response events. The line with dots is the response to target events embedded in regular series. The other five lines are the other five experimental conditions; their ERPs did not show any statistically reliable difference in the P300 time-frame. Time is in ms, potentials are in μV .

Conclusive Remarks

According to Newell (1990), in order to maintain its adaptive function the inferential system must develop and preserve an isomorphism to the environment: that is, it must be as correct as possible in anticipating future states of the environment. Confirmed and disconfirmed anticipations are crucial events for the fine-tuning of the system: confirmed anticipations strengthen our confidence toward our current knowledge, whereas disconfirmed anticipations trigger knowledge revision and search for novel information. The human attentional system has developed a general orienting mechanism that gives priority to these crucial events. As the reported experiments show, attention is focused on anticipated events, and it is defocused and redistributed in the case that the anticipation is later discon-

firmed by a contrasting state of affairs. When the inferential processes cannot compute any anticipation, that is when the local environment is random (or perceived as such), the two clues are not available: as a consequence, performance is less efficient.

The effect of confirmed and disconfirmed anticipations on the orienting of attention were observed in tasks where there was no statistical ground whatsoever for endorsing any expectation. The human inferential system is highly sensitive to statistical covariations in the environment (Holyoak & Spellman, 1993; Nisbett, 1993; Holland, Holyoak, Nisbett & Thagard, 1986), but *de facto* it uses regularities to detect them: the inductive use of perceived, apparently informative, regularities is so compelling that it is not suppressed even when perceived regularities are not statistically valid predictors of the responses. In other words, inferences are based on perceived regularities in the environment; attention is driven by inferences; therefore, attention is driven by perceived regularities in the environment, even uninformative ones. This finding corroborates our conjecture that giving priority to confirmed and disconfirmed events is a *spontaneous* tendency of the attentional system. But, is it entirely automatic, or can it be voluntarily inhibited? The present results do not settle this issue.

The illustrated mechanisms are likely very general, because they function in a very similar way for the perceptual and symbolic tasks that we used. This is substantially consistent with the hypothesis by Posner and Petersen (1990) according to which the orienting of attention is a modular function whose characteristics do not depend on the type of input stimuli, and with Posner's previous proposal (1980) that understanding the mechanisms of spatial orienting could help to understand the mechanisms of orienting to higher-level structures. However, in all the experiments that we reported, the symbolic task involved tracking an arithmetic series. This is a possible limitation, inasmuch there is evidence that numbers are represented in a continuous, quantity-based analogical format functionally isomorphic to physical lines (Dehaene, 1992; Gallistel & Gelman, 2000; Whalen, Gallistel, & Gelman, 1999; Moyer & Landauer, 1967), and that this functional similarity may involve actual similarities of the neural substrate of the respective representations (Zorzi, Priftis & Umiltà, 2002): that is, the strikingly similar behavioral and electrophysiological patterns that we described could be at least partly caused by commonalities in the representational format of visual trajectories and arithmetic series. Accordingly, further research is required in order to test whether similar inference-driven orienting mechanisms can be observed also when inferences concern expectations that are outside the physical or numerical domain. For example: does the abrupt disconfirmation of an expectation in the sentence "We hold these truths to be self-evident, that all men are

created equal, that they are endowed by their Creator with certain unalienable rights", re-orient attention, possibly as an attempt to draw some alternative meaning out of the sentence? Further research is needed in order to clarify this matter.

References

- Bar-Hillel, M., & Wagenaar, W.A. 1991. The perception of randomness. *Advances in Applied Mathematics* 12: 428-454.
- Berry, D. (Ed.). 1997. *How implicit is implicit learning? Debates in psychology*. New York: Oxford University Press.
- Biederman, I., Mezzanotte, R.J., & Rabinowitz, J. 1982. Scene perception: Detecting and judging objects undergoing relational violations. *Cognitive Psychology* 14: 143-177.
- Chapman, L.J. 1967. Illusory correlation in observational report. *Journal of Verbal Learning and Verbal Behavior* 6: 151-155.
- Cherubini, P., Burigo, M., & Bricolo, E. 2005. Inference-driven attention in symbolic and perceptual tasks: Biases toward expected and unexpected inputs. *Quarterly Journal of Experimental Psychology*, published on-line by prE-view, 29th August. Printed version forthcoming.
- Cherubini, P., Castelvechchio, E., & Cherubini, A.M. 2005. Generation of hypotheses in Wason's 2-4-6 task: An information theory approach. *Quarterly Journal of Experimental Psychology* 58A: 309-332.
- Castelvechchio, E., Vallesi, A., Mapelli, D., & Cherubini, P. 2004. *Perceptual and numeric expectations: Overt and covert effects*. Presented at the XXIII congress of the experimental section of the Italian Psychological Association, Sciacca, September.
- Dehaene, S. 1992. Varieties of numerical abilities. *Cognition* 44: 1-42
- Diener, D., & Thompson, W.B. 1985. Recognizing randomness. *American Journal of Psychology* 98: 433-447.
- Falk, R., & Konold, C. 1997. Making sense of randomness: Implicit encoding as a basis for judgment. *Psychological Review* 104: 301-318.
- Fiedler, K. 2000. Beware of samples! A cognitive-ecological sampling theory of judgement biases. *Psychological Review* 107: 659-676.
- Gallistel, C.R., & Gelman, R. 2000. Nonverbal numerical cognition: From reals to integers. *Trends in Cognitive Sciences* 4: 59-65.
- Hamilton, D.L., Dugan, P., & Troler, T.K. 1985. The formation of stereotypic beliefs: Further evidence for distinctiveness-based illusory correlation. *Journal of Personality and Social Psychology* 48: 5-17.
- Hamilton, D.L., & Gifford, R.K. 1976. Illusory correlation in interpersonal perception: A cognitive basis of stereotypic judgments. *Journal of Experimental Social Psychology* 12: 392-407.

- Hawley, K.J., Johnston, W.A., & Farnham, J.M. 1994. Novel popout with nonsense strings: Effects of predictability of string length and spatial location. *Perception & Psychophysics* 55: 261-268.
- Hillstrom, A.P., & Yantis, S. 1994. Visual motion and attentional capture. *Perception & Psychophysics* 55: 399-411.
- Holland, J.H., Holyoak, K.J., Nisbett, R.E., & Thagard, P.R. 1986. *Induction: Processes of inference, learning, and discovery*. Cambridge, MA: MIT Press.
- Holyoak, K.J., & Spellman, B.A. 1993. Thinking. *Annual Review of Psychology* 44: 265-315.
- Jacoby, L.L., & Dallas, M. 1981. On the relationship between autobiographical memory and perceptual learning. *Journal of Experimental Psychology: General* 110: 306-340.
- Johnson, R. 1988. The amplitude of the P300 component of the event-related potential: Review and synthesis. In P. K. Ackles, J.R. Jennings, & M. G. H. Coles (Eds.), *Advances in psychophysiology*, Vol. 11I (pp. 69-137). Greenwich, London: JAI Press.
- Johnston, W.A., & Hawley, K.J. 1994. Perceptual inhibition of expected inputs: The key that opens closed minds. *Psychonomic Bulletin & Review* 1: 56-72.
- Johnston, W.A., & Schwarting I.S. 1997. Novel popout: An enigma for conventional theories of attention. *Journal of Experimental Psychology: Human Perception & Performance* 23: 622-631.
- Johnston, W.A., Schwarting, I.S., & Hawley, K.J. 1996. Novel popout, perceptual inhibition, and the stability/plasticity dilemma. In A.F. Kramer, M.G.H. Coles, & G.D. Logan (Eds.), *Converging operations in the study of visual selective attention* (pp. 315-335). Washington, DC: American Psychological Association.
- Klein, R. 1988. Inhibitory tagging system facilitates visual search. *Nature* 334: 430-431.
- Klein, R., & MacInnes, W.J. 1999. Inhibition of return is a foraging facilitator in visual search. *Psychological Science* 10: 346-352.
- Lang, S., & Kotchoubey, B. 2002. Brain responses to number sequences with and without active task requirement. *Clinical Neurophysiology* 113: 1734-1741.
- Marr, D. 1982. *Vision*. New York: Freeman and Co.
- McKenzie, C.R.M. 1994. The accuracy of intuitive judgment strategies: Covariation assessment and Bayesian inference. *Cognitive Psychology* 26: 209-239.
- Moyer, R. & Landauer, T. 1967. Time required for judgments of numerical inequality. *Nature* 215: 1519-1520.
- Neisser, U. 1976. *Cognition and Reality*. San Francisco: Freeman.
- Newell, A. 1990. *Unified theories of cognition*. Cambridge, MA: Harvard University Press.
- Nisbett, R.E. 1993. *Rules for reasoning*. Hillsdale, NJ: Erlbaum.
- Pena, M., Bonatti, L., Nespor, M., & Mehler, J. 2002. Signal driving computation in speech processing. *Science* 298: 604-607.
- Polich, J. 1985. N400s from sentences, semantic categories, number and letter strings? *Bulletin of the Psychonomic Society* 23: 361-364.
- Posner, M.I. 1980. Orienting of attention. The VIIth Sir Frederic Bartlett Lecture. *Quarterly Journal of Experimental Psychology* 32: 3-25.
- Posner, M.I., & Cohen, Y. 1984. Components of visual orienting. In H. Bouma & D.G. Bouwhuis (Eds.), *Attention and Performance X* (pp. 531-536). Hillsdale, NJ: Erlbaum.
- Posner, M.I., & Petersen, S.E. 1990. The attention system of the human brain. *Annual Review of Neurosciences* 13: 25-42.
- Posner, M.I., Rafal, R.D., Choate, L.S., & Vaughan, J. 1985. Inhibition of return: Neural basis and function. *Cognitive Neuropsychology* 2: 211-228.
- Posner, M.I., Snyder, R.R.C., & Davidson, B.J. 1980. Attention and the detection of signals. *Journal of Experimental Psychology: General* 109: 160-174.
- Pratt, J., & McAuliffe, J. 2002. Inhibition of return in visual marking? The importance of the interstimulus interval and the type of search task. *Visual Cognition* 9: 869-888.
- Pratt, J., O'Donnell, C., & Morgan, A. 2000. The role of fixation location in inhibition of return. *Canadian Journal of Experimental Psychology* 54: 186-195.
- Rauschenberger, R., & Yantis, S. 2001. Attentional capture by globally defined objects. *Perception & Psychophysics* 63: 1250-1261.
- Remington, R.W., Johnston, J.C., & Yantis, S. 1992. Involuntary attentional capture by abrupt onsets. *Perception & Psychophysics* 51 : 279-290.
- Rensink, R.A. 2002. Change Detection. *Annual Review of Psychology* 53:245-277
- Rips, L.J. 2001. Two kinds of reasoning. *Psychological Science* 12: 129-134
- Seger, C.A. 1994. Implicit learning. *Psychological Bulletin* 115: 163-196.
- Sommer, W., Matt, J., & Leuthold, H. 1990. Consciousness of attention and expectancy as reflected in event-related potentials and reaction times. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 16: 902-915.
- Squires, K., Wickens, C., Squires, N., & Donchin, E. 1976. The effect of stimulus sequence on the waveform of the cortical event-related potential. *Science* 193: 1142-1145.
- Whalen, J., C.R. Gallistel, & R. Gelman. 1999. Nonverbal counting in humans: The psychophysics of number representation. *Psychological Science* 10: 130-137.
- Yantis, S. 1996. Attentional capture in vision. In A.F. Kramer, M.G.H. Coles, & G.D. Logan (Eds.), *Converging operations in the study of visual selective attention* (pp. 45-76). Washington, D.C.: American Psychological Association.
- Zorzi, M., Priftis, K., & Umiltà, C. 2002. Neglect disrupts the mental number line. *Nature* 417: 138-139.