# CANADIAN LABORATORIES / LABORATOIRES CANADIENS

# On the Control of Attention

Raymond Klein
Dalhousie University
2008 CSBBC Donald O. Hebb Distinguished Award/Prix Donald O. Hebb 2008 de la SCCCSC

An early interest in cognitive processes led me to study with Mike Posner from whom I acquired the intellectual tools to follow Hebb's (1949) advice that "Everyone knows that attention and set exist so we had better get the skeleton out of the closet and see what can be done with it." Using variants of the model task Posner developed for exploring the control of visual attention we have demonstrated that endogenous shifts of attention are not generated by unexecuted oculomotor activation, that endogenous and exogenous shifts of attention are fundamentally different on a variety of dimensions and that an aftermath of exogenous (but not endogenous) orienting, inhibition of return, facilitates search by encouraging orienting to novel items. A research strategy for understanding ambiguous forms of orienting (e.g., that controlled by conspecific gaze) is proposed.

Keywords: attention, endogenous, exogenous, inhibition of return, eye movements

It is a great honour to be the recipient of the 2008 Canadian Society for Brain, Behaviour and Cognitive Science D. O. Hebb award. As an ardent Hebb-admirer and proponent of the society bestowing this honour I am especially grateful.<sup>1</sup> As most of you know, I am a cognitive psychologist whose primary interest is human attention. I have a secondary interest in reading and literacy. Moreover, as Hebb encouraged us to do, I understand that mental states and mental processes are implemented in and by the brain. Although we can develop quite respectable theories of cognitive processes without any consideration of the underlying neural processes, there is something exciting and, especially from a clinical perspective, very important, that is missing until our theories link the neural with the psychological levels of analysis. In Hebb's terms, we should be "putting our money" on a "neuropsychological" theory.

Most of my time has been spent doing and supervising basic cognitive and cognitive neuroscience research. However, recently, I have become increasingly involved in applying the methods and findings of human experimental psychology to real world problems of individuals such as those suffering from dyslexia, attention deficit/hyperactivity disorder (ADHD), problem gambling, and brain damage because of stroke; and to real-world issues such as counterfeit detection, eyewitness testimony, road and offshore safety.

I graduated from high school in 1964 and decided to do my undergraduate work at the State University of New York (SUNY) at Stony Brook because this was the only school I applied to that accepted me. At the time, my dad was an accountant with several brokerage firms as clients and when I was in high school, I worked for several summers at one such firm (Laidlaw & Co.). Perhaps because

of this background I started out as an economics major. I first encountered Hebb's *Organisation of Behaviour: A Neuropsychological Theory* in one of my Psychology classes at Stony Brook.<sup>2</sup>

This early exposure to Hebb, plus some great psychology professors, shifted my interests to minds from markets, and in 1969 (just as the United States involvement in Vietnam was peaking) I

<sup>1</sup> I want to thank all those with whom I have collaborated over the years: The kind of research I like to do depends on your willingness to work with me. I hope you enjoy this work as much as I do. I also want to thank Don Hebb for coming back to Nova Scotia and Dalhousie University upon his retirement from McGill. And Richard Brown, Vince DiLollo, Gail Eskes, Tracy Taylor, David Shore, and all the other people who nominated me for this award. Thank you to my family for putting up with my 9 a.m. to 2 p.m. schedule. In the loving home environment created by my parents, Max and Edith, there was an unwavering encouragement of curiosity and respect for knowledge. There was never any doubt that I would continue my education. And, like many of you, I chose a profession in which I continue to go to school almost every day and I continue to learn-from my students and colleagues. When Dr. Patricia McMullen and I published our edited volume: Converging methods for understanding reading and dyslexia, my appreciation was made explicit in the book's dedication "to the pursuit of education for its own sake which our parents taught us and we hope to pass on to our students." A special thanks goes to Michael Posner whose heart and mind provided a uniquely nurturing environment for budding psychological scientists, like me, eager to learn how to study the mind and its organ. The topic and title of this paper have their origins in Posner's Bartlett Lecture: On the orienting of attention (Posner, 1980).

<sup>2</sup> Much later (in 1977), when Hebb retired from McGill and returned to his undergraduate alma mater, Dalhousie University, as an honorary professor, I got to know him personally. When I wrote the introductory chapter (Klein, 1980a), *D. O. Hebb: An Appreciation*, to the book that Peter Jusczyck and I edited from the colloquium series we held in honour of Hebb's return to Dalhousie (Jusczyk & Klein, 1980), *On the Nature of Thought: Essays in Honour of D. O. Hebb*, I really began to appreciate the magnitude of his legacy.

Raymond Klein, Department of Psychology, Dalhousie University. Correspondence concerning this article should be addressed to Raymond Klein, Department of Psychology, Dalhousie University, Halifax, Nova B3H 4J1, Canada. E-mail: Ray.Klein@dal.ca

graduated from SUNY at Stony Brook with a double major in psychology and economics. Considering graduate school, and expressing to my professors, Roger Schvanaveldt and Marvin Levine, a desire to "understand how the mind works" I was advised to "go study with Mike Posner" who was doing the most imaginative work on this difficult question. I applied to a few graduate programs, but was only accepted by the University of Oregon to work with Mike Posner.

While at Stony Brook, I dated Marilyn Sands and we continued to correspond after my move to Oregon. Our long-distance correspondence turned into a lifelong love affair and we decided to get married after I completed my first year at Oregon. Being philosophically opposed to the Vietnam War, and generally, to killing people, I had applied to New York Selective Service for official status as a conscientious objector (CO). Although this was not granted, I was under the impression that I was eligible to appeal the decision.

Joining Posner's group was, initially, simply a new experience against which I had nothing to compare. I realise now, how amazing it was. It was not only that Mike is brilliant and innovative; always ahead of and leading the field. He is also a wonderful person. I met with Mike in his office and he laid out two research paths I could follow: I could explore the coordination of visual and name codes in the processing of letters (extending work Posner was already famous for through studies that used his lettermatching task) or I could explore the coordination of visual and kinesthetic codes in the control of movement. I barely knew what a kinesthetic code was, and so, as in Frost's poem, I chose the path "less travelled by" for my graduate research.

As planned, after one year in the master's program I returned to New York City to get married, and was unexpectedly drafted as a result of the lottery: I was "ordered" to report for service on my wedding day! Fortunately, an American Civil Liberties Union lawyer got the induction order quashed on a technicality and so the wedding could go on as planned. When the Selective Service's earlier denial of my application for conscientious objector status was eventually overturned, I proposed for my alternative service to conduct psychological research (funded by the U.S. Office of Education) under Dr. Posner's supervision. COs must do work in the "public service" for which they are not well paid. Not knowing what to do, New York Selective Service wrote to Oregon Selective Service, which wrote back, "We've never assigned anyone to the Department of Psychology at the University of Oregon, but we don't see why you can't," and I was able to continue, and eventually complete my graduate training as a conscientious objector. I know that Mike got a kick out of the regular reports he had to file with the Selective Service on my progress.

Working primarily with Mike Posner, but also influenced by Posner's close friend and colleague, Steve Keele, (and a wonderful group of graduate student colleagues) I earned my M.A. in 1972 and Ph.D. in 1974 in the general area of human attention and performance. My graduate training emphasised two approaches in which Posner was a pioneer: mental chronometry (Posner, 1978) and the use of computers in psychological research. Reflecting this latter, yet today little known, leadership role, in the first graduate class I remember taking (at Mike's suggestion) I learnt assembly language programming for Digital Equipment Corp.'s PDP-09 minicomputer, which enabled me two write the program that

controlled a servo-motor and oscilloscope for my Master's thesis experiments.

As a strategy for exploring how the mind works, mental chronometry is most strongly associated with the use of reaction time (RT) as a dependent variable, but this is simply a part of the strategy which also uses time as an independent variable and looks at the timing of dependent variables other than motor responses, including brain activity (e.g., Posner, Klein, Summers, & Buggie, 1973).

#### Visual Dominance

The topic I chose for my dissertation was visual dominance:

"Findings from a variety of experimental paradigms reveal that the subjective reports and performance of human subjects tend to be controlled by visual information. Although this phenomenon, usually referred to as visual dominance, has been most extensively studied by creating an artificial discrepancy between vision and kinesthesis . . . its occurrence is not restricted to perceptual judgements made in the presence of visual-kinesthetic conflict." (Klein, 1977, p. 365–6)

Having been exposed to Posner's mental chronometry strategy, my challenge was how to apply the strategy to something that had hitherto been explored using psychophysical and phenomenological methods. Exemplifying the phenomenological approach, Gibson (1943) reported that when touching a straight edge while wearing prisms that make it look curved, one's hand feels as if it is moving along a curved edge.

Posner had a knack for steering his students down fruitful paths while giving us the excitement of making our own discovery. He suggested that I look at a fencing study by Timothy Jordan and this gave me an idea for one of the four experiments that eventually made up my dissertation. The other three (not discussed here) were inspired by seminal studies by David LaBerge and Charles Eriksen. Jordan (1972) measured the RT (to the start of muscle activity) of three groups of fencers to begin a disengage and lunge in response to the movement of a mechanical opponent. Each group experienced the "attack" differently:

### a. Vision plus kinesthesis (V+K)

Their foil was touching a mechanical foil and they had free vision

### b. Vision (V)

Their foil was not several centimeters away from the mechanical foil and they have free vision (here, initially at least, the information would be only visual)

### c. Kinesthesis (K)

Same as (a) but the participant was blindfolded.

After practise it was not surprising that responses in the K condition were faster than in the V condition: We could expect this from what was known about simple reaction time to stimuli from different modalities (Woodworth, 1938). The surprising result (see top row of Table 1) was that RT in the V+K condition was much slower than in the K condition. Normally when two inputs signal the same response AND assuming (1) both inputs are attended and contribute to performance, and (2) there is some overlap in the distribution of RTs to each of the inputs when presented sepa-

Table 1
Results From Studies of Reaction Time to Unimodal (Visual, Kinesthetic) and Bimodal (Visual Plus Kinesthetic) Reaction Time (RT)

Study	Visual RT	Kinesthetic RT	V+K RT
Jordan (1972) block 10	650	590	642
Klein (1977) E2 Pure	317	248	261
Klein (1977) E2 Mixed	337	260	243

*Note.* In Jordan's study, different groups of participants experienced the three different conditions. In Klein's study, participants experienced the three conditions. In separate (pure) blocks or experienced them randomly intermixed in one (mixed) block.

rately, we would expect some statistical redundancy gain: RT should be faster than to either input when presented alone. Under the same assumptions, except in the absence of overlap in the distribution of RTs from these two inputs, we would expect RT to match that of the faster distribution. Therefore, Jordan's finding implies that the two, redundant, inputs were not jointly contributing to performance in the V+K condition.

In my follow-up to Jordan's study I sought to determine whether visual dominance over kinesthesis was automatic or the result of a strategic bias to selectively attend vision.

"Two contrasting explanations for this asymmetry might be proposed (see Figure 1). One explanation, emphasising "hardware," claims that the nervous system is wired up so that visual inputs suppress kinesthetic inputs at the level of conscious attention. This might be accomplished through inhibition of the kinesthetic pathways by visual inputs (see Figure la). Alternatively, automatic suppression of kinesthesis could occur if vision has more copious connections to attention than does kinesthesis (see Figure 1b). This would result in occlusion of kinesthesis during bimodal stimulation because attention is limited in capacity. Either "hardware" view would imply that vision should capture attention whenever visual and kinesthetic stimuli are presented at the same time. An alternative explanation, emphasising "software," attributes visual dominance to a bias or strategy to selectively attend vision whenever visual information seems sufficient to perform the task (see Figure 1c). The bias could be habitual and need not be deliberate . . . This view implies that visual dominance will not be found when the bias is discouraged." (Klein, 1977, p. 369)

In Jordan's experiment the three conditions were administered to separate participants. Perhaps when a participant knows that visual information can be relied upon (such as when it is present on every trial), vision is selectively attended, even if performance isn't optimised through this biased strategy. Therefore, in my experiment there were two groups: one experienced the three conditions in separate blocks of trials; whereas the other group experienced the three conditions randomly intermixed in a single block of trial. I reasoned that if the dominance were strategic then by mixing V, K, and V+K trials attention would have to be divided between vision and touch to accommodate the unimodal trials. In that case, mixing the conditions would eliminate the dominance effect. On the other hand, under either nonstrategic view mixing these trials should have no effect on the visual dominance that, by hypothesis, simply happens when information about an event is simultaneously available from vision and touch. In the pure blocks condition (see middle row of Table 1) I replicated the important finding from Jordan: V+K > K. In contrast, in the mixed blocks (see bottom row of Table 1), I found clear evidence for a redundancy gain; precisely what would be expected if information from both modalities was being attended to and utilised without deterioration. Other findings, including the higher error rates in the presence of tactile-kinesthetic inputs were well handled by an explanation that included the assumption that the tactile inputs were more automatically alerting than the visual inputs.

The results from this experiment, thus, strongly supported the strategic explanation. These findings, combined with converging evidence from Mary Joe Nissen's dissertation led to an information processing explanation for visual dominance (Posner, Nissen, & Klein, 1976). One reason for highlighting this early project is that it illustrates a distinction that is fundamental in psychology and that has guided much of my own research: that between data-driven processes over which we have little or no control (reflexive or automatic processes) and those top-down processes over which do have strategic control (voluntary processes) (for a neo-Hebbian example of this interest, see Trappenberg, Dorris, Munoz, & Klein, 2001).

I graduated from the University of Oregon in 1974. As a result of my experience in the Posner laboratory, and influenced by other Oregonians (notably Steve Keele, Fred Attneave, and Wayne Wicklegren) and Hebb, I learnt to think and conduct research in certain ways, one might say, with certain biases that I have not outgrown. Consequently, I have a strong interest in the components of attention (Posner & Boies, 1971) and their role in perfor-

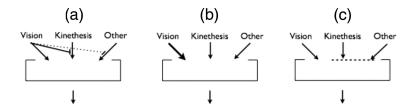


Figure 1. Three possible mechanisms for visual dominance. Sensory information from vision, kinesthesis, and other modalities are shown converging upon a central attentional mechanism. (a) Activation of the visual pathway inhibits the kinesthetic pathway and perhaps that of other modalities as well. (b) Vision has more copious connections to the attentional mechanism. (c) The dotted line represents a movable gate that is under the strategic control of the subject and which can be set to allow any modality easy access to attention while blocking other modalities from consciousness. Redrawn from Klein (1977).

mance (Keele, 1973); I work within an information processing view of human behaviour, wherein it is respectable to hypothesise a homunculus so long as you don't require him or her to do everything (Attneave, 1961); I have a proclivity to use mental chronometry (Posner, 1978) as a primary tool for revealing how the mind works (and a conviction that speed of responding cannot be understood without simultaneous consideration of the accuracy of responding, Wicklegren, 1977); and, recognising that the brain is the organ of mind, I believe that one route to understanding the mind is through understanding how cognitive processes are implemented by assemblies of neurons (Hebb, 1949).

In 1974, I was offered a position by the Psychology Department at Dalhousie University. I also had a job offer from the University of Connecticut, but I had never heard of Dalhousie and Marilyn and I liked the idea of an adventure. Therefore, accepting the offer, we took a plane to Vancouver and the railroad across Canada to Halifax. We naively imagined we would live in a lighthouse by the sea and although we did not and do not, we are surrounded by the ocean and, despite the short summers (or is it the long winters?) we love and still live in Halifax.

Over the years, my research program has been eclectic. This is partly a character trait; and partly because of the relatively free reign I have given to my students whose interests over the years have pulled me in new and unexpected directions. To minimise the eclecticism of this paper, I will focus on the control of visual attention.

## Orienting

Orienting most obviously involves turning receptors toward the source of stimulation. These receptors are not always visual, though this discussion will focus on visual orienting. Moreover, since Helmholtz we have known that even without an overt movement of the eyes we can selectively attend to different regions of visual space. The selection or prioritization that can occur in auditory information processing began to be actively pursued in the 1950s. This research was summarised and integrated into a seminal theoretical framework by Broadbent (1958). It was extended to the visual modality in the 1960s and 1970s by investigators such as Sperling, Posner, Eriksen, and Treisman. Owing to William James (1890) and Posner (cf., Posner, Snyder, & Davidson, 1980) the spotlight (or beam of attention) metaphor became popular as a way to capture the hypothesised properties of visual attention, and consequently as a device for stimulating research.

So, when we talk about visual orienting we need to distinguish whether our eyes or an internal "pointer" may be shifted in space thereby selecting what information will be given processing priority; a distinction most often referred to as overt versus covert orienting.

A second distinction concerns how orienting is controlled. Is orienting controlled intentionally, by what might be referred to an effort of will; and in the absence of direct stimulation from the to-be-attended location? On the other hand, is it controlled reflexively in response to such pathway activation? The labels most frequently used to distinguish between these modes of control are: Voluntary versus reflexive; top-down versus bottom-up; endogenous versus exogenous. A good deal of the research that my collaborators and I have engaged in over the years sought to characterise the four modes of orienting (see Figure 2) that are

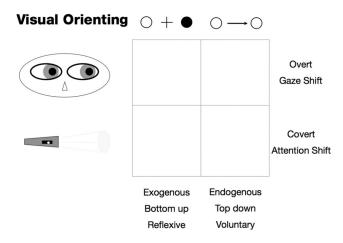


Figure 2. Reflexive and voluntary control of overt (eye movements) and covert (attention) yield four modes of orienting that were distinguished by Posner (1980).

implied by the orthogonal combination of endogenous versus exogenous control of overt versus covert orienting and to discover how these modes of orienting may be related.

### Model Task

Because many of the studies I will describe use one version or another of the model task developed by Posner for exploring covert visual orienting, I will begin with a brief review of how this task works, with reference to Figure 3. Time flows from left to right and a trial might begin with three horizontally arranged boxes. The lines connecting the boxes illustrate all the possible state transitions. Possible probabilities of the different transition sequences are shown at the ends of the lines. Endogenous control of orienting is illustrated in the upper panel; exogenous control is illustrated in the lower panel. In both protocols a fixation display is followed by a cue display and sometime later by a presentation of a target (e.g., asterisk) or on a catch trial no target is presented. When purely endogenous control is studied, the cue (e.g., an arrow pointing left or right) is informative about the upcoming location of the target. In this illustration, targets are four times as likely to occur at the cued location than the uncued location (80:20). Because it has recently been demonstrated that central arrows, even when they are uninformative (e.g., Ristic & Kingstone, 2006; Tipples, 2002) may generate an attention shift (presumably reflexively and because of prior spatial behaviour in response to arrows) researchers interested in purely endogenous control are urged to use as endogenous cues stimuli for which such a previous history is unlikely. When purely exogenous control is studied, a peripheral event (e.g., a brightening of one of the boxes) that is uninformative about the upcoming target location is presented at or near one of the possible target locations. When the task calls for a simple or choice manual or verbal response to the target, and no eye movements are executed, the cue elicits covert orienting. When the task calls for a saccade in response to the target, the cue activates or prepares overt orienting. In both procedures trials with neutral cues are indicated by thin solid lines between the cue and target; trials with valid cues are indicated by thick solid lines; trials with invalid cues are indicated by thick dotted lines; and catch trials are indicated by thin dashed lines.

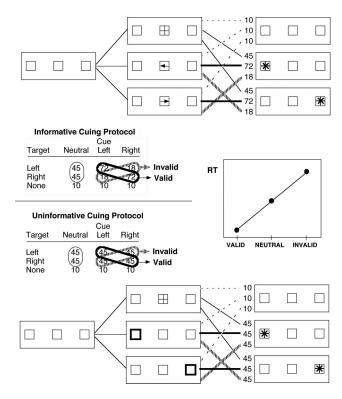


Figure 3. Two versions of the model task developed by Posner for studying covert orienting of visual attention are illustrated here. Endogenous cueing with an 80:20 cue validity is illustrated at the top of the figure; exogenous cueing with a 50:50 cue validity is illustrated at the bottom. Prototypical RT data are shown in the middle. Redrawn from Klein (2005).

The prototypical pattern of results when reaction time is the dependent variable is that valid RT < neutral RT < invalid RT. The neutral minus valid and invalid minus neutral differences were referred to as benefits and costs, respectively, of allocating attention. Because truly neutral conditions can be difficult to construct (cf. Jonides & Mack, 1984) some investigators have focussed simply on the overall cueing effect (invalid RT minus valid RT) that is sometimes called "costs plus benefits." In some studies, peripheral cues are informative, yielding a hybrid protocol in which the participant voluntarily attends in the direction of a peripheral cue that would normally elicit orienting exogenously. This is most often used in studies of patients (e.g., see Losier & Klein, 2001) wherein, because of the scarcity of participants the authors may be seeking to maximise the chances of observing a cueing effect. Sound as this rationale might be, it creates a confound such that differences between patients and controls cannot be confidently attributed to endogenous or exogenous control.

# Is Endogenous Covert Orienting Simply Unexecuted Oculomotor Activation?

My first concrete proposal in the world of orienting (which I have referred to as the "oculomotor readiness hypothesis," or OMRH) was about the role of the system responsible for overt orienting in the implementation of voluntary/endogenous control of covert orienting (Klein, 1980b). There were two streams of

scholarship behind it, both of which I had been exposed to during my undergraduate and graduate programs. One was neuroscientific data from the laboratories of Peter Schiller (Schiller & Koerner, 1971; Schiller & Stryker, 1972) and Robert Wurtz (Wurtz & Mohler, 1974) on the control of eye movements and attention. The other was the idea that motor processes might play an important role in perception (Festinger, Ono, Burnham, & Bamber, 1967; Hebb, 1949; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). Putting these streams of thought together, I proposed that endogenous covert shifts of attention might be mediated by preparation of an eye movement to foveate the to-beattended location:

"When attention to a particular location is desired, the observer prepares to make an eye movement to that location; the oculomotor readiness, via as yet unknown feedforward pathways, has the effect of enhancing processing in or from sensory pathways dealing with information from the target location." (Klein, 1980b, p. 262)

At the time, I knew that when eye movements were actually executed there was a corresponding shift of attention (Bryden, 1961; Crovitz & Daves, 1962; Posner, 1980). More recently, this has been clearly demonstrated even when endogenous signals are used to generate a saccadic eye movement (Hoffman & Subramaniam, 1995; Shepherd, Findlay, & Hockey, 1986). However, there was no data on the linkage between shifts of attention and preparation of eye movements in the absence of their execution. Because, by definition, covert orienting takes place in the absence of eye movements, a new kind of study was needed to explore the OMRH. In 1979 I presented two dual-task experiments at Attention & Performance VIII (Klein, 1980b) that tested the OMRH. In one experiment, the endogenous cueing protocol with manual responses to targets (covert orienting) was used to encourage a shift of attention and occasional stimuli requiring an eye movement were used to probe the state of oculomotor activation. In the other experiment, participants made eye movements in one direction for an entire block of trials whenever a particular target stimulus appeared in either peripheral location. Occasionally, a different target requiring a manual response was presented to probe the locus of attention. If covert shifts of attention are accomplished by preparing an eye movement, then probing the eye movement system during a covert orienting study should reveal faster saccades in the prepared direction. Conversely, when the participant has prepared an eye movement to foveate a particular location, then probing the locus of attention (with occasional manual detection targets) should reveal that it is at the to-befixated location. Both of these predictions were disconfirmed.

Several improvements were made to these studies in Amanda Pontefract's Master's thesis (published in Klein & Pontefract, 1994). Importantly, verbal commands were used to prepare an eye movement when eye movements were the primary task and similar commands were used to signal that an eye movement should be executed (whether eye movements were the primary or probe task). The results are shown in Figure 4. Here it can be seen that when attention had been covertly shifted to the left or the right of fixation, there was no preparation of a corresponding eye movement. Indeed, in this condition there was a small, but significant trend for eye movements to be initiated more quickly in the direction opposite to that which was attended, suggesting that participants may have sometimes been inhibiting the natural ten-

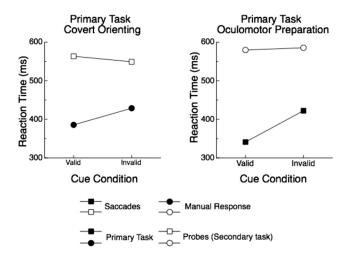


Figure 4. Dual task reaction time data from Klein and Pontefract (1994).

dency to move the eyes in the attended direction. In addition, when eye movements were prepared to the location to the left or right of fixation, there was no corresponding shift of attention as measured with the manual detection probes. Hunt and Kingstone (2003) replicated both of these findings while extending our methods by using a speeded oculomotor task in combination with an unspeeded, accuracy-based task to assess attention. With the cooperation of Hunt, I (Klein, 2004a) generated a scatterplot of the data from their experiment in which the overt and covert cueing effects from each dual task condition were plotted against each other. If the OMRH were correct then individuals who showed stronger cueing effects of one type (e.g., overt primary task) should also show stronger cueing effects of the other type (e.g., covert probe task). Instead, the actual correlation (although not significant, -.229) was negative, providing converging evidence for the conclusion that the OMRH is simply wrong.

What I called the "oculomotor readiness hypothesis" lives on under the name later given to it by Rizzolatti and colleagues (Rizzolatti, Riggio, Dascola, & Umilta, 1987): premotor theory. So long as the "pre" in premotor means "before" then, as noted above, there is excellent evidence that covert shifts of attention precede overt shifts of gaze. However, when the "pre" in premotor is about preparation in the absence of overt execution, then I do not believe that it is generally true: Normally when we want to move our attention without moving our eyes, the oculomotor system is simply suppressed. If it were not, our effort to keep orienting covert would likely fail.

Three caveats are in order. First, whereas endogenous preparation of an eye movement may not entail a covert shift of attention, as noted earlier, voluntary execution of an eye movement (even in the absence of peripheral stimulation) causes a shift of attention that occurs before the eyes reach the target (Hoffman & Subramaniam, 1995; Posner, 1980). Second, when covert attention is controlled exogenously there will necessarily be activation of the oculomotor system because stimuli that capture attention also capture oculomotor behaviour. Third, neuroimaging studies typically reveal a considerable amount of overlap between the brain structures activated when overt and covert orienting are activated endogenously (see, e.g., Corbetta et al., 1998). I have addressed the pertinence of this finding for the OMRH (and premotor theory) from several perspectives:

"First, in order to attend without looking, there will be inhibition of the overt orienting machinery. Present neuroimaging methods may be unable to distinguish between neural activity whose objective is disabling from neural activity whose objective is enabling. Second, there is considerable nonoverlap. The fact that we normally move our attention and our eyes together may be partly responsible for the overlap, while the ability to move them independently may be mediated by the structures that appear to be activated separately. Finally, different neural circuits in the same neural structures may, via different projection patterns, control covert and overt orienting endogenously." (Klein, 2004a, p. 38)

## One Spotlight or Two?

We have known since Jonides (1981) that there are important differences between endogenous and exogenous control of covert orienting. Exogenous control is relatively fast; endogenous control is slow; exogenous control is relatively automatic; endogenous control is effortful. The field, quite naturally, assumed that the difference between attention when controlled endogenously versus exogenously was simply a matter of transportation: Two different ways of getting the same machinery to an object or location in space. On the contrary, two findings from my laboratory and a host of findings in the literature suggest that different attentional resources or machinery may be oriented covertly when the control is endogenous versus exogenous.

The first finding was made by Kevin Briand in his master's thesis (reported in Briand & Klein, 1987) in which he asked: "Is Posner's beam the same as Treisman's glue?" In Treisman's feature integration theory (FIT), when a search target is defined by a conjunction of features, attention is hypothesised to be required to "glue" together the features that are present at the same location Treisman & Gelade, 1980). In contrast, targets defined by single features can be identified without attention. Briand's participants decided if one of two letters presented to the left or right of fixation was the letter R. In the feature search condition the distractors were drawn from the set PB; in this case the R could be distinguished from the distractors by its diagonal feature, and according to FIT, attention would not be needed to determine whether or not an **R** was present. In the conjunction condition, the distractors were drawn from the set  $\mathbf{PQ}$ . In this case, when the R is not present attention is needed to know this because in the absence of attention the features from the PQ array may combine to form an R (an "illusory conjunction"). On each trial an informative spatial cue was presented before the appearance of two letters on one side of fixation along with two counterbalancing ""s on the other side (to minimise the chances that the appearance of the letters would capture attention). We predicted that if the Posner'esque beam that was oriented by the spatial cue was the same as the Treisman'esque glue that performs feature integration, then there would be an interaction between cue condition (valid vs. invalid) and whether search was based on a single feature versus a conjunction of features. In particular, the cueing effect should be greater for conjunction search than for feature search. Supporting a "yes" answer to our question, this is precisely what we found when the cues were presented in the periphery (see Prinzmetal, Presti, & Posner, 1986, for a similar result). However, supporting a "no" answer we found an additive pattern when the cue was an arrow presented at fixation (see Figure 5, top pair of graphs). Responding to suggestions made by Tsal (1989, see also Briand &

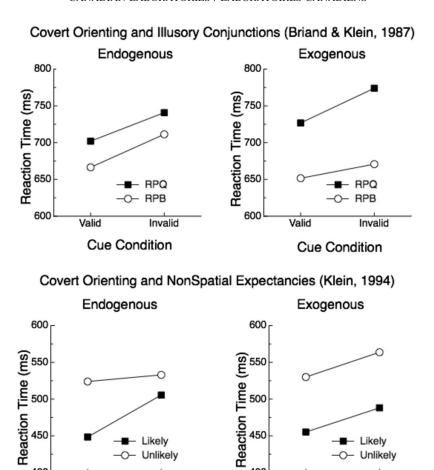


Figure 5. The upper panels illustrate data from Experiments 2 (central cue) and 4 (peripheral cue) from Briand and Klein (1987) in which the cueing paradigm was combined with a feature or conjunction search task. The lower panels illustrate data from Klein (1994) in which the spatial cueing paradigm was combined with likely and unlikely targets.

400

Valid

Unlikely

Invalid

Cue Condition

Klein, 1989), Briand (1998) extended this work by using colour/ form conjunctions while varying the informativeness and timing of the cues. Key results from comparable versions of both of Briand's studies are shown in Table 2. Here it can be seen that whenever the cue was presented in the periphery (whether it was or was not informative and whether the cue-target SOA was short or long) there was a greater cueing effect for conjunction search than for feature search—just as would be expected if the attentional beam captured by the peripheral cue performed the gluing function hypothesised by Triesman and Gelade (1980). However, when the cue was an informative arrow presented at fixation, there was not a significant interaction seen in Briand & Klein, 1987 (Experiment 3 was in the opposite direction). Thusly, behavioural evidence demonstrates that when visual attention is exogenously controlled "Posner's beam is Triesman's glue" and when attention is endogenously controlled "Posner's beam is not Triesman's glue." One solution to this paradox is to assume that there are two different beams.

400

Valid

The second finding grew out of a puzzling pattern of results in my 1980 paper (Klein, 1980b). Participants whose attention had been endogenously directed by an arrow cue to the left or right in preparation for a target calling for a manual response were occasionally required to make a prosaccade or an antisaccade in response to a different, "probe," target. Saccadic RT to these eye movement targets did not benefit when these targets were presented at a location that was endogenously attended. My graduate student, Edward Hansen, and I (Klein & Hansen, 1987) initially referred to this as "spotlight failure" because if, like a spotlight, mental resources had been allocated in response to the arrow cue then any stimulus presented within its "beam" should benefit from these resources. In Hansen's dissertation (reported in Klein & Hansen, 1990), arrow cues were informative about the location of a likely target (for different participants, either the brightening or dimming of one of the peripheral markers was likely and the other change was unlikely), and participants were required to make a two-choice response to discriminate between the likely and unlikely targets (dimming or brightening). The unlikely stimulus target (luminance change) showed little or no evidence of a spatial cueing effect while the likely stimulus showed a robust one. In other words, the pattern of results suggested that the "spotlight"

Unlikely

Invalid

Cue Condition

Table 2
Methodological Parameters and Findings (Cuing Effects Are Presented in the Columns Labeled I-V, for Invalid Minus Valid, See Figure 3) From Briand's Studies of the Relationship Between Endogenous and Exogenous Orienting and Feature Versus Conjunction Target Search Tasks

Experiment	Cue location	Cue validity	Cue-target SOA (ms)	I-V feat.	I-V conj.	Significant interaction?
Briand & Klein (1987) E2	Central	80:20	1000	45	39	No
Briand & Klein (1987) E3	Central	80:20	1000	85	54	No
Briand & Klein (1987) E4	Peripheral	80:20	160	19	48	Yes
Briand (1998) E1	Peripheral	80:20	167	31	59	Yes
Briand (1998) E2	Central	80:20	167	5	10	No
Briand (1998) E3	Central	80:20	500	49	60	No
Briand (1998) E4	Peripheral	80:20	500	56	84	Yes
Briand (1998) E5a	Peripheral	75:25	167	20	38	**
Briand (1998) E5a	Peripheral	50:50	167	32	44	Yes*
Briand (1998) E5b	Peripheral	50:50	500	42	57	Yes

*Note.* \* There was a significant interaction between cue condition and type of search task that did not interact (F < 1) with cue validity in E5 that implies separate "Yes"s for the two conditions of E5a.

was only working for the likely stimulus. Later (Klein, 1994), I replicated this pattern using a size change discrimination task (expansion vs. contraction). Importantly, when I simply changed the cues from arrows at fixation to a peripheral luminance increase (while using the same targets and cue-target probabilities) an additive pattern (equivalent cueing effects for both the likely and unlikely size changes (see Figure 5, bottom pair of graphs) was obtained. Behavioural evidence, thus, demonstrates that when visual attention is exogenously controlled "the beam illuminates all stimuli" whether they are likely or not; whereas, when attention is endogenously controlled "the spotlight fails" in the sense that only the likely stimulus-response pairs seem to benefit from attention. Another way of stating this is that nonspatial expectancies (target identity and response likelihood) are additive with exogenously controlled attention while these expectancies interact with endogenously controlled attention.

The pattern of errors that participants made in response to the unlikely stimuli in the endogenous cueing tasks (Klein & Hansen, 1990; Klein, 1994) was consistent with decision-level effects of attention, whereby when a target appeared at the cued location there was a significant tendency to misclassify it as the more likely stimulus. Following Broadbent's (1987) advice Klein and Hansen (1990) developed a simple accumulator model with thresholds representing response criteria. The pattern of results with endogenous cueing and likely/unlikely stimuli could be produced within this model by either a purely decision-level effect (response criterion settings) or by a combination of such a decision-level effect and signal enhancement because of endogenous attention. Although Klein and Hansen favoured the combination explanation, which is why they suggested that the effect of the spotlight had been "masked" rather than eliminated for the unlikely stimuli, their behavioural data was indecisive. It was not until I explored this question using ERPs in collaboration with Todd Handy and Ron Mangun (Handy, Green, Klein, & Mangun, 2001) that it was possible to firmly endorse one view. Our finding—that while the unlikely target showed no RT benefit when it appeared at the cued location (relative to the uncued location), these targets still showed enhancement of attention-sensitive early ERP componentsstrongly confirmed the spotlight masking view.

As noted by Klein and Shore (2000) the pattern of results from my studies with Briand and Hansen represents a conceptual double dissociation, that is illustrated in Figure 5 and summarised in the upper two rows of Table 3: When controlled endogenously, attention interacts with nonspatial expectancies and is additive with the possibility of illusory conjunctions; when controlled exogenously, the opposite pattern is obtained: attention is additive with nonspatial expectancies and interacts with the possibility of illusory conjunctions. An information processing interpretation of these findings is offered in Figure 6. Considering the neuroscientific implications of this double dissociation I suggested that "the anterior and posterior attention systems—which have been distinguished on the basis of cognitive neuroscientific evidence—may underlie, respectively, endogenous and exogenous orienting. . ." (Klein, 1994, p. 178). Neuroimaging studies have since qualified this relatively coarse suggestion while confirming the basic idea of isolable subsystems (e.g., Hahn, Ross, & Stein, 2006; Kincade, Abrams, Astafiev, Shulman, & Corbetta, 2005).

# Further Dissociations

There are a variety of other ways in which attention differs when under endogenous versus exogenous control (see the remainder of

Table 3
When Under Endogenous Versus Exogenous Control
"Attention" Has Dramatically Different Effects and Properties

Effect	Endogenous control	Exogenous control
Interacts with		
opportunities for		
illusory conjunctions?	No	Yes
Interacts with nonspatial		
expectancies?	Yes	No
Extra costs when attention		
crosses a meridian?	Yes	No
How does attention alter		
the spatial Stroop		
effect?	Increases	Decreases
Is there a disengage		
deficit?	No (very small)	Yes
Does it generate illusory		
line motion?	No	Yes
Does it generate inhibition		
of return?	No	Yes

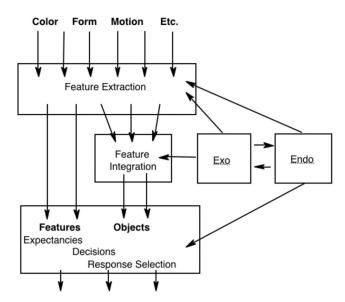


Figure 6. Flow diagram showing putative information processing stages involved in exogenous and endogenous covert orienting. Redrawn from Klein (1994).

Table 3). When attention is controlled endogenously, reaction time to an invalidly cued target shows extra costs (compared to a shift of equal size) when the hypothetical shift of attention (from the cued location to the target) must cross either the vertical or horizontal meridian (Rizzolatti et al., 1987). This meridional crossing effect is not obtained when peripheral cues are used (Reuter-Lorenz & Fendrich, 1992).

When participants are responding to the direction in which an arrow is pointing they are faster if the arrow's location with respect to fixation is compatible with the arrows' direction. This "spatial Stroop" effect is increased for targets presented at endogenously attended locations and it decreased for targets presented at exogenously attended locations (Funes, Lupiañez, & Milliken, 2007).

Patients suffering from unilateral neglect after damage to the right parietal cortex show a dramatic increase in the time to detect targets in their poor field after a peripheral cue to their good field. Posner and colleagues (Posner, Walker, Freidrich, & Rafal, 1984) referred to this as a disengage deficit—as if once they had allocated attention to a location in the good field the patient had difficulty disengaging attention from this location to move it to a target in the poor field. Reviewing the literature on the disengage deficit, Losier and Klein (2001) point to evidence suggesting that it is very reduced if not absent when attention is controlled endogenously.

When a line that is presented all at once is preceded by a cue at one end of the line, the line appears to be drawn across the display away from the cue (e.g., Hikosaka, Miyauchi, & Shimojo, 1991; Schmidt & Klein, 1997). This illusory experience of motion within the line is observed when a peripheral cue captures attention exogenously, but not when attention is directed endogenously by an informative central cue (Christie & Klein, 2005). If attention were the cause of illusory line motion, then this finding would add to the evidence that there are two different beams of attention recruited by exogenous and endogenous control, respectively. However, it is also possible that it is primarily a nearby peripheral stimulus that is the key factor that

generates illusory line motion. By showing that a peripheral stimulus that is unlikely to capture attention (because it is one peripheral element of an array centered at fixation) generates almost the same illusory line motion experience as the same peripheral element when presented alone Fuller and Carrasco (2009) provided strong evidence in favour of stimulation rather than exogenous attention as the generator for illusory line motion.

Posner and Cohen (1984) published a seminar paper in which an inhibitory aftermath of orienting was discovered (for reviews, see Klein, 2000; Taylor & Klein, 1998). Using the exogenous version of the model task developed by Posner and illustrated in Figure 3, immediately after an uninformative peripheral cue, and presumably, because of attentional capture by the cue, reaction time to targets near the cue is faster than to targets in the opposite location. However, when there is no reason for the participant to keep attention at the cued location, if the onset of the target is delayed so that it appears 250 milliseconds or more after the onset of the cue, the RT difference reverses and targets are responded to more slowly when they are presented at the originally cued location. Posner and colleagues (Posner et al., 1985) later named this "inhibition of return" (IOR) to reflect their interpretation that after attention was disengaged from such a peripherally cued location attention was inhibited from returning there. Inhibition of return has been a preoccupation of my laboratory and some of our research will be covered in the next section. In the context of this discussion of endogenous/exogenous differences it is noteworthy that inhibition of return is not observed following the removal of attention from a location that had been attended endogenously (Posner & Cohen, 1984; Rafal et al., 1989) and once generated it is additive with effects of endogenous orienting (Berlucchi, Chelazzi, & Tassinari, 2000; Lupianez, Decaix, Siéroff, Chokron, Milliken, & Bartolomeo, 2004). These findings suggest that IOR is an inhibitory after-effect of exogenous orienting that affects subsequent exogenous orienting.

These are some of the differences that support the suggestion that there may be two beams of attention. Readers may be aware of others. Based on such differences it has been suggested that:

"... endogenous and exogenous control over visual orienting recruit qualitatively different attentional resources to analyse information at the cued location. An important implication is that claims about the spatial or temporal properties of visual orienting, about its susceptibility to different forms of brain damage, about its development, and so forth, must be restricted to the type of control used to elicit the orienting. To be complete, such claims should be buttressed by evidence collected with both endogenous and exogenous control." (Klein, 1994, p. 178)

I believe that this remains sound advice.

### Inhibition of Return

My colleagues and I have explored the causes and effects (Taylor & Klein, 1998, 2000), development (MacPherson, Moore, & Klein, 2003), timecourse (Klein, 2004a; Klein, Castel, & Pratt, 2006), spatial distribution (Klein, Christie, & Morris, 2005), neural implementation (Dorris, Klein, Everling, & Munoz, 2002), functional significance (Klein, 1988; Klein & Dukewich, 2006; Klein & MacInnes, 1999; MacInnes & Klein, 2003), and other attributes (Ivanoff & Klein, 2001, 2003, 2004, 2006) of IOR. We have looked for IOR in the

pigeon (Gibson, Juricevic, Shettleworth, Pratt, & Klein, 2005) where we failed to find it and in the monkey (Dorris, Taylor, Klein, & Munoz, 1999) where we did find it. Because we have written several reviews of different aspects of IOR (Ivanoff & Klein, 2006; Ivanoff, Klein, & Lupiañez, 2002; Klein, 2000, 2004b, 2005; Klein & Dukewich, 2006; Klein & Ivanoff, 2008; Klein, Munoz, Dorris, & Taylor, 2001; Lupiañez, Klein, & Bartolomeo, 2006; Taylor & Klein, 1998), in this section I will highlight a few ideas and findings that fit best with the theme of this paper.

One reason for interest in IOR is its hypothesised functional significance. Consider inspecting a scene for a visual target. Computational models hypothesise a "saliency map" (receiving bottom-up + top-down activation). A "winner-take-all" algorithm causes the most activated object or location in the scene to be attended. When this item is not the target the search continues until the target is found. Without a mechanism to reduce the salience of the just inspected item, it will remain the most salient, the selection algorithm will perseverate and the search will fail. Inhibition of return, which was first observed in a simple cueing experiment (Posner & Cohen, 1984) has been proposed to be this mechanism (Itti & Koch, 2001; Klein, 1988).

In 1988, I developed the search-followed-by-probe procedure to test this hypothesis. After a difficult search task, for which according to Treisman and Gelade (1980), and others—movement of the attentional beam would have been necessary, RT to probes in the locations of distractors was slower than to probes in previously empty locations. This delay was considerably greater than what was found after an easy search task for which the target pops out and consequently a serial inspection by attention is not required. This pattern, which was subsequently replicated by Takeda and Yagi (2000) and Müller and von Mühlenen (2000), is precisely what would be predicted by my proposal that IOR was the foraging facilitator that decreases the salience of array items once they had been inspected. With Joe MacInnes, I explored IOR in the context of an oculomotor search task using the Where's Waldo drawings of Martin Hanford (Klein & MacInnes, 1999; MacInnes & Klein, 2003). We found that eve movements to probe targets presented during (Klein & MacInnes, 1999) or after (MacInnes & Klein, 2003) search of a complex scene were relatively slow when these probes were placed in locations that had been previously fixated. This slowing, which showed a very clear gradient, was eliminated if the scene was removed when the probe was presented. This dependence of the inhibitory effect upon the presence of the scene (which was also demonstrated by Takeda and Yagi [2000] and Müller and von Mühlenen [2000]) strongly suggests that in these search studies the inhibition had been coded into a representation of the scene itself. This way, removal of the scene would remove the inhibitory tags. Converging evidence that overt orienting leaves a trail of inhibitory tags has been provided in a series of "follow the dots" studies from Art Kramer's laboratory (e.g., McCarley, Wang, Kramer, Irwin, & Peterson, 2003).

Two flavors of IOR were demonstrated in Tracy Taylor's dissertation (reported in Taylor & Klein, 2000) that looked for IOR in 24 conditions (for 9–10 of which IOR had been reported in the literature). There is not space to go into all 24 conditions, but importantly, the target on some trials was a peripheral event and on others it was a central arrow. For either target, a localisation response was required. The results are quite easy to describe. When no eye movements were made (neither to the cue nor to the

target) IOR had an attentional/perceptual flavor: For IOR to be observed there had to be a peripheral target. However, so long as the oculomotor system was not "turned off" during the experiment (an eye movement was made to the cue or to the target), IOR had a motoric flavor—if it was observed with a peripheral target, then it was also observed with a central arrow target.

Whether or not saccades are executed, oculomotor activation and oculomotor pathways seem to play a special role in causing IOR (Rafal et al., 1989; Sapir, Soroker, Berger, & Henik, 1999) that, at least in some situations, seems to be implemented as a bias against responding in the cued direction (Ivanoff & Klein, 2001; Klein & Taylor, 1994). It is not the case that the peripheral pathway that was stimulated by the cue is adapted or fatigued because IOR seems to be coded in environmental (Maylor & Hockey, 1985), object (Tipper, Driver, & Weaver, 2002) coordinates, when the eyes or the cued object move between the cue and the target (or in scene coordinates when search is of a complex scene) and IOR has been observed cross-modally between all pairs of vision, audition and touch (Spence, Lloyd, McGlone, Nicholls, & Driver, 2000). According to Dukewich (2009) IOR is essentially habituation of the orienting response (Sokolov, 1960). Although there is a tendency to confuse habituation with sensory adaptation, as Dukewich notes habituation can take place at any level of the nervous system. This property of habituation allows her account to be entirely consistent with the motoric, cross-modality and environmental/object coding findings. Moreover, because the orienting response occurs to novel events, and its habituation would tend to discourage orienting toward the familiar, the Dukewich interpretation is entirely consistent with the functional interpretation of IOR as a novelty seeking (Posner & Cohen, 1984) and search facilitating (Klein, 1988) mechanism.

# A Research Strategy

I want to end by suggesting a research strategy that builds on the foregoing. There are numerous forms of orienting that are, along the endogenous/exogenous dimension, somewhat ambiguous.

- 1. Perhaps one of the most interesting of these is conspecific gaze direction (in the developmental literature this has been labelled, joint visual attention). When a face you are looking at looks away, you have a tendency to look in that direction. Is this form of orienting, which does not stimulate (directly) the to-be-attended location, but which seems to be somewhat reflexive (cf. Friesen & Kingstone, 1998), more like endogenous or exogenous orienting? The "yardstick" for this assessment would be to study this form of orienting using the manipulations listed in Table 3. For a preliminary implementation of this strategy with reference to gaze cueing, see McKee, Christie, & Klein, 2007). There are a variety of other ambiguous forms of orienting that could be subjected to this strategy; some of these are listed below.
- When a novel or familiar item captures your attention there was something in the periphery to attend, but what makes this item different from the other candidates is information stored in long-term memory.

- The attention of an anxious or depressed individual that seems to be captured by threatening or negative stimuli, respectively.
- The attention that is launched in the direction of, and in advance of, a shift of gaze, when that shift is controlled endogenously.
- The reflexive component of orienting in the direction of an uninformative central arrow.
- 6. Inhibition of return

Readers may think of other ambiguous forms of attention to add to this list. It is my suggestion that by discovering how each form behaves with regard to the properties like those listed in Table 3, their similarities and differences will be revealed, a taxonomy of covert orienting could be confidently generated, and a better understanding of the control of attention would be achieved.

Understanding the convergence of bottom-up and top-down signals in the control of behaviour and thought is one of the great problems for neuro-psychological science. Because visual attention is a "model system" for exploring this convergence, I believe that the studies described in this paper and the research strategy suggested here, in conclusion, can shed valuable light on this problem.

### Résumé

Un intérêt de longue date pour les processus cognitifs m'a amené à étudier avec Mike Posner, ce qui m'a permis d'hériter des outils intellectuels pour suivre le conseil de Hebb (1949) selon lequel « tout le monde sait que l'attention et les processus centraux existent, alors nous devons sortir le squelette du placard et voir ce que l'on peut en faire ». En utilisant des variantes de la tâche modèle que Posner a développé pour explorer le contrôle de l'attention visuelle, nous avons démontré que les déplacements endogènes de l'attention ne sont pas générés par une activité oculomotrice non exécutée, que les déplacement endogènes et exogènes de l'attention different fondamentalement selon une variété de dimensions et qu'un effet résiduel de l'orientation exogène (mais pas endogène), l'inhibition du retour, facilite la recherche en encourageant l'orientation vers de nouveaux items. Une stratégie de recherche pour comprendre les formes d'orientation ambiguës (par ex., celle qui est contrôlées par le regard conspécifique) est proposée.

Mots-clés : attention, endogène, exogène, inhibition du retour, déplacements oculaires

## References

- Attneave, F. (1961). Comments: In defense of homunculi. In Rosenblith (Ed.), *Sensory communication* (pp. 777–781). Cambridge: The MIT Press.
- Berlucchi, G., Chelazzi, L., & Tassinari, G. (2000). Volitional covert orienting to a peripheral cue does not suppress cue-induced inhibition of return. *Journal of Cognitive Neuroscience*, 12, 648–663.
- Briand, K., & Klein, R. M. (1987). Is Posner's beam the same as Treisman's glue?: On the relationship between visual orienting and feature integration theory. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 228–247.
- Briand, K., & Klein, R. M. (1989). Has feature integration theory come

- unglued? A reply to Tsal. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 401–406.
- Briand, K. A. (1998). Feature integration and spatial attention: More evidence of a dissociation between endogenous and exogenous orienting. *Journal of Experimental Psychology: Human Perception and Per*formance, 24, 1243–1256.
- Broadbent, D. E. (1958). Perception and communication. Elmsford, NY: Pergamon Press.
- Broadbent, D. E. (1987). Simple models for experimentable situations. In P. Morris (Ed.) *Modeling cognition* (pp. 160–185). New York: Wiley.
- Bryden, M. P. (1961). The role of post-exposural eye movements in tachistoscopic perception. Canadian Journal of Psychology, 15, 220–225.
- Christie, J., & Klein, R. M. (2005). Does attention cause illusory line motion? *Perception & Psychophysics*, 67, 1032–1043.
- Corbetta, M., Akbudak, E., Conturo, T. E., Snyder, A. Z., Ollinger, J. M., Drury, H. A., et al. (1998). A common network of functional areas for attention and eye movements. *Neuron*, 21, 761–773.
- Crovitz, H. F., & Daves, W. (1962). Tendencies to eye movement and perceptual accuracy. *Journal of Experimental Psychology*, 63, 495–498.
- Dorris, M. C., Klein, R. M., Everling, S., & Munoz, D. P. (2002). Contribution of the primate superior colliculus to inhibition of return. *Journal of Cognitive Neuroscience*, 14, 1256–1263.
- Dorris, M. C., Taylor, T., Klein, R. M., & Munoz, D. P. (1999). Influence of previous visual stimulus or saccade on saccadic reaction times in monkey. *Journal of Neurophysiology*, 81, 2429–2436.
- Dukewich (2009). The habituation account of inhibition of return. Psychonomic Bulletin & Review, 62, 238–251.
- Festinger, L., Ono, H., Burnham, C. A., & Bamber, D. (1967). Efference and the conscious experience of perception. *Journal of Experimental Psychology (Monograph)*, 74, 1–36.
- Friesen, C. K., & Kingstone, A. (1998). The eyes have it! Reflexive orienting is triggered by nonpredictive gaze. *Psychonomic Bulletin & Review*, 5, 490–495.
- Fuller, S., & Carrasco, M. (in press). Perceptual consequences of visual performance fields: The case of the line motion illusion. *Journal of Vision*.
- Funes, M. J., Lupiáñez, J., & Milliken B. (2007). Separate mechanisms recruited by exogenous and endogenous spatial cues: Evidence from a spatial Stroop paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, 33, 348–362.
- Gibson, J. J. (1943). Adaptation, after-effect and contrast in the perception of curved lines. *Journal of Experimental Psychology*, 16, 1–31.
- Gibson, B. M., Juricevic, I., Shettleworth, S. J., Pratt, J., & Klein, R. M. (2005). Looking for inhibition of return in pigeons. *Learning & Behavior*, 33, 296–308.
- Hahn, B., Ross, T. J., & Stein, E. A. (2006). Neuroanatomical dissociation between bottom-up and top-down processes of visuospatial selective attention. *Neuroimage*, 32, 842–853.
- Handy, T., Green, V., Klein, R. M., Mangun, G. R. (2001). Combined expectancies: ERPs reveal early benefits of spatial attention that are absent in reaction time. *Journal of Experimental Psychology: Human Perception and Performance*, 27, 303–317.
- Hebb, D. O. (1949). The organization of behaviour: A neuropsychological theory. Oxford: Wiley.
- Hikosaka, O., Miyauchi, S., & Shimojo, S. (1991). Focal visual attention produces motion sensation in lines. *Investigative Opthalmology & Vi*sual Science, 32, 716.
- Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception and Psychophysics*, 57, 787–795.
- Hunt, A., & Kingstone, A. (2003). Covert and over voluntary attention: Linked or independent? Cognitive Brain Research, 18, 102–105.
- Itti, L., & Koch, C. (2001). Computational modeling of visual attention. *Nature Reviews Neuroscience*, 2, 1–10.
- Ivanoff, J., & Klein, R. M. (2001). The presence of a nonresponding

- effector increases inhibition of return. *Psychonomic Bulletin and Review*, 8, 307–314.
- Ivanoff, J., & Klein, R. M. (2003). Orienting of attention without awareness is affected by measurement-induced attentional control settings. *Journal of Vision*, 3, 32–40.
- Ivanoff, J., & Klein, R. M. (2004). Stimulus-response expectancies and inhibition of return. Psychonomic Bulletin & Review, 11, 542–550.
- Ivanoff, J., Klein, R. M., & Lupiañez, J. (2002). Inhibition of return interacts with the Simon effect. *Perception & Psychophysics*, 64, 318–327.
- Ivanoff, J., & Klein, R. M. (2003). Orienting of attention without awareness is affected by measurement-induced attentional control settings. *Journal of Vision*, 3, 32–40.
- Ivanoff, J., & Klein, R. M. (2006). A speed-accuracy analysis of inhibition of return in go/no-go and choice-RT tasks. *Journal of Experimental Psychology: Human Perception and Performance*, 32, 908–919.
- James, W. (1890). Principles of psychology (2 volumes) New York: Henry Holt
- Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J. B. Long & A. D. Baddeley (Eds.), *Attention & performance IX* (pp. 187–203). Hillsdale, NJ: Erlbaum.
- Jonides, J., & Mack, R. (1984). On the cost and benefit of cost and benefit. Psychological Bulletin, 96, 29–44.
- Jordan, T. C. (1972). Characteristics of visual and proprioceptive response times in the learning of a motor skill. *Quarterly Journal of Experimental Psychology*, 24, 536–543.
- Jusczyk, P., & Klein, R. M. (Eds.). (1980). The Nature of Thought: Essays in honor of D. O. Hebb. Hillsdale, N.J.: Erlbaum Assoc.
- Keele, S. W. (1973). Attention and human performance. Pacific Palisades, CA: Goodyear Publishing.
- Kincade, J. M., Abrams, R. A., Astafiev, S. V., Shulman, G. L., & Corbetta, M. (2005). An event-related functional magnetic resonance imaging study of voluntary and stimulus-driven orienting of attention. *Journal of Neuroscience*, 25, 4593–4604.
- Klein, R. M. (1977). Attention and visual dominance: A chronometric analysis. *Journal of Experimental Psychology: Human Perception and Performance*, 3, 365–378.
- Klein, R. M. (1988). Inhibitory tagging system facilitates visual search. *Nature*, 334, 430–431.
- Klein, R. M. (1980a). D. O. Hebb: An appreciation. In P. Jusczyk & R. M. Klein (Eds.), On the nature of thought: Essays in honour of D. O. Hebb (pp. 1–18). Hillsdale, NJ: Erlbaum.
- Klein, R. M. (1980b). Does oculomotor readiness mediate cognitive control of visual attention. In R. Nickerson (Ed.), *Attention and performance VIII* (pp. 259–276). Hillsdale, NJ: Erlbaum.
- Klein, R. M. (1994). Perceptual-motor expectancies interact with covert visual orienting under endogenous but not exogenous control. *Canadian Journal of Experimental Psychology*, 48, 151–166.
- Klein, R. M. (2000). Inhibition of return. Trends in Cognitive Sciences, 4, 138–147.
- Klein, R. M. (2004a). On the control of orienting. In M. I. Posner (Ed.), Cognitive neuroscience of attention (pp. 29-44). New York: Guilford Press.
- Klein, R. M. (2004b). Orienting and inhibition of return. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (3rd ed, pp. 545–560). Cambridge, MA: MIT Press.
- Klein, R. M. (2005). On the role of endogenous orienting in the inhibitory aftermath of exogenous orienting. In U. Mayr, E. Awh, & S. Keele (Eds.), Developing Individuality in the human brain: A feschrift for Michael Posner (pp. 45–64). Washington, DC: APA Books.
- Klein, R. M., Castel, A., & Pratt, J. (2006). The effects of memory load on the timecourse of inhibition of return. *Psychonomic Bulletin & Review*, 13, 294–299.
- Klein, R. M., Christie, J., & Morris, E. (2005). Vector averaging of inhibition of return. Psychonomic Bulletin & Review, 12, 295–300.

- Klein, R. M., & Dukewich, K. (2006). Does the inspector have a memory? Visual Cognition, 14, 648–667.
- Klein, R. M., & Hansen, E. (1987). Spotlight failure in visual orienting. Bulletin of the Psychonomics Society, 25, 447–450.
- Klein, R. M., & Hansen, E. (1990). Chronometric analysis of spotlight failure in endogenous visual orienting. *Journal of Experimental Psychol*ogy: Human Perception and Performance, 16, 790–801.
- Klein, R. M., & Ivanoff, J. (2008). Inhibition of return. Scholarpedia, 3, 3650.
- Klein, R. M., & MacInnes, W. J. (1999). Inhibition of return is a foraging facilitator in visual search. *Psychological Science*, 10, 346–352.
- Klein, R. M., & McMullen, P. (1999). Converging Methods for Understanding Reading and Dyslexia. Cambridge: MIT Press.
- Klein, R. M., Munoz, D. P., Dorris, M. C., & Taylor, T. L. (2001).
  Inhibition of return in monkey and man. In C. Folk & B. Gibson (Eds.),
  Attraction, distraction, and action: Multiple perspectives on attention capture (pp. 27–47). Amsterdam: Elsevier.
- Klein, R. M., & Pontefract, A. (1994). Does oculomotor readiness mediate cognitive control of visual attention? Revisited! In C. Umiltà & M. Moscovitch (Eds.), Attention & performance XV: Conscious and unconscious processing (pp. 333–350). Cambridge, MA: MIT Press.
- Klein, R. M., & Shore, D. I. (2000). Relations among modes of visual orienting. In S. Monsell & J. Driver (Eds.), Attention & performance XVIII: Control of cognitive processes (pp. 195–208). Cambridge, MA: MIT Press.
- Klein, R. M., & Taylor, T. (1994). Categories of cognitive inhibition with reference to attention. In D. Dagenbach & T. Carr (Eds.), *Inhibitory* processes in attention, memory & language (pp. 113–150). New York: Academic Press.
- Liberman, A. M., Cooper, F. S., Shankweiler, D. P., & Studdert-Kennedy, M. (1967). Perception of the speech code. *Psychological Review*, 74, 431–461.
- Losier, B. J., & Klein, R. M. (2001). A review of the evidence for a disengage operation deficit following parietal lobe damage. *Neuro-science and Biobehavioral Reviews*, 25, 1–13.
- Lupiañez, J., Decaix, C., Siéroff, E., Chokron, S., Milliken, B., & Bartolomeo, P. (2004). Independent effects of endogenous and exogenous spatial cueing: Inhibition of return at endogenously attended target locations. *Experimental Brain Research*, 159, 447–457.
- Lupiañez, J., Klein, R. M., & Bartolomeo, P. (2006). Inhibition of return: Twenty years after. Cognitive Neuropsychology, 23, 1003–1114.
- MacInnes, W. J., & Klein, R. M. (2003). Inhibition of return biases orienting during the search of complex scenes. *The Scientific World Journal*, 3, 75–86.
- MacPherson, A., Klein, R. M., & Moore, C. (2003). Inhibition of Return in Children and Adolescents. *Journal of Experimental Child Psychology*, 85, 337–351.
- Maylor, E. A., & Hockey, R. (1985). Inhibitory component of externally controlled covert orienting in visual space. *Journal of Experimental Psychology: Human Perception and Performance*, 11, 777–787.
- McCarley, J. S., Wang, R. X. F., Kramer, A. F., Irwin, D. E., & Peterson, M. S. (2003). How much memory does oculomotor search have? Psychological Science, 14, 422–426.visual attention. Journal of Experimental Psychology: Human Perception and Performance, 20, 478–499.
- McKee, D., Christie, J., & Klein, R. M. (2007). On the uniqueness of attentional capture by uninformative gaze cues: Facilitation interacts with the Simon effect and is rarely followed by IOR. *Canadian Journal* of Experimental Psychology, 21, 293–303.
- Müller, H., & von Muhlenen, A. (2000). Probing distractor inhibition in visual search: Inhibition of return. *Journal of Experimental Psychology: Human Perception and Performance*, 26, 1591–1605.
- Posner, M. I. (1978). *Chronometric explorations of mind*. Oxford, England: Erlbaum.
- Posner, M. I. (1980). Orienting of attention. Quarterly Journal of Experimental Psychology, 32, 3–25.

- Posner, M. I., & Boies, S. J. (1971). Components of attention. *Psychological Review*, 78, 391–408.
- Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. Bonwhuis (Eds.), Attention and performance X: Control of language processes (pp. 551–556). Hilldale, NJ: Erlbaum.
- Posner, M. I., Klein, R. M., Summers, J., & Buggie, S. (1973). On the selection of signals. *Memory & Cognition*, 1, 2–12.
- Posner, M. I., Nissen, J. J., & Klein, R. M. (1976). Visual dominance: An information processing account of its origins and significance. *Psychological Review*, 83, 157–171.
- 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, C. R. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, 109, 160–174.
- Posner, M. I., Walker, J. A., Friedrich, F. J., & Rafal, R. D. (1984). Effects of parietal injury on covert orienting of visual attention. *Journal of Neuroscience*, 4, 1863–1874.
- Prinzmetal, W., Presti, D. E., & Posner, M. I. (1986). Does attention affect visual feature integration? *Journal of Experimental Psychology: Human Perception and Performance*, 12, 361–370.
- Rafal, R. D., Calabresi, P. A., Brennan, C. W., & Sciolto, T. K. (1989). Saccade preparation inhibits reorienting to recently attended locations. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 673–685.
- Reuter-Lorenz, P. A., & Fendrich, R. (1992). Oculomotor readiness and covert orienting: Differences between central and peripheral precues. *Perception and Psychophysics*, 52, 336–344.
- Ristic, J., & Kingstone, A. (2006). Attention to arrows: Pointing to a new direction. *Quarterly Journal of Experimental Psychology*, 59, 1921– 1930.
- Rizzolatti, G., Riggio, L., Dascola, I., & Umilta, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. *Neuropsychologia*, 25, 31–40.
- Sapir, A., Soroker, N., Berger, A., & Henik, A. (1999). Inhibition of return in spatial attention: Direct evidence for collicular generation. *Nature Neuroscience*, 2, 1053–1054.
- Schiller, P. H., & Koerner, E. (1971). Discharge characteristics of single units in superior colliculous of the alert rhesus monkey. *Journal of Neurophysiology*, 34, 930–936.
- Schiller, P. H., & Stryker, M. (1972). Single unit recording and stimulation in superior colliculis of alert rhesus monkey. *Journal of Neurophysiol*ogy, 35, 915–924.
- Schmidt, W. C., & Klein, R. M. (1997). A spatial gradient of acceleration

- and temporal extension underlies three illusions of motion. *Perception*, 26, 857–874.
- Shepherd, M., Findlay, J. M., & Hockey, R. J. (1986). The relationship between eye movements and spatial attention. *Quarterly Journal of Experimental Psychology*, 38A, 475–491.
- Sokolov, E. N. (1960). Neuronal models and the orienting reflex. In M. A. Brazier (Ed.), *The central nervous system and behavior* (pp. 187–276). New York: J. Macy.
- Spence, C., Lloyd, D., McGlone, F., Nicholls, M. E. R., & Driver, J. (2000). Inhibition of return is supramodal: A demonstration between all possible pairings of vision, touch, and audition. *Experimental Brain Research*, 134, 42–48.
- Takeda, Y., & Yagi, A. (2000). Inhibitory tagging in visual search can be found if search stimuli remain visible. *Perception and Psychophysics*, 62, 927–934.
- Taylor, T., & Klein, R. M. (2000). Visual and motor effects in inhibition of return. *Journal of Experimental Psychology: Human Perception and Performance*, 26, 1639–1655.
- Taylor, T. L., & Klein. R. M. (1998). On the causes and effects of inhibition of return. *Psychonomic Bulletin and Review*, 5, 625–643.
- Tipper, S. P., Driver, J., & Weaver, B. (1991). Object-centred inhibition of return of visual attention. *Quarterly Journal of Experimental Psychology* A, 43, 289–298.
- Tipples, J. (2002). Eye gaze is not unique: Automatic orienting in response to noninformative arrows. *Psychonomic Bulletin & Review*, 9, 314–318.
- Trappenberg, T. P., Dorris, M. C., Munoz, D. P., & Klein, R. M. (2001).
  A model of saccade initiation based on the competitive integration of exogenous and endogenous signals in the superior colliculus. *Journal of Cognitive Neuroscience*, 13, 256–271.
- Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. Cognitive Psychology, 12, 97–136.
- Tsal, Y. (1989). Do illusory conjunctions support the feature integration theory? A critical review of theory and findings. *Journal of Experimen*tal Psychology: Human Perception and Performance, 15, 394–400.
- Wicklegren, W. (1977). Speed accuracy trade-off and information processing dynamics. Acta Psychologica, 41, 67–85.
- Woodworth, R. S. (1938). Experimental psychology. Oxford, England: Holt
- Wurtz, R. H., & Mohler, C. W. (1974). Selection of visual targets for the initiation of saccadic eye movements. *Brain Research*, 71, 209–214.

Received March 8, 2009 Accepted March 10, 2009