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Human Perception: A Science of Synergy

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This article is loosely based on an address given to the Canadian Society for Brain, Behaviour and Cognitive Science at their annual meeting on June 7, 2013, in honor of being named the 2013 Donald O. Hebb Distinguished Contribution Award Winner.

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I was honoured to receive the 2013 Hebb Award in recognition of my research efforts in the field of human perception. My first reaction to this news was to question whether I had really been working long enough to be considered for this award. I did not consider myself in the same company as previous winners, who I saw as a really impressive lot. My second reaction was to develop weak knees when I realised this meant delivering the annual Canadian Society for Brain, Behaviour and Cognitive Science lecture. When I told my wife of my apprehension, she asked, "What's the big deal? You give talks on your research all the time." My response was, "Yes, of course, but this home audience really knows!" I therefore humbly accepted this honour, with the understanding that I would deliver the talk as a summary of my research efforts over several decades. In my mind, it is still very much a work in progress. I look forward to your feedback.

I am old enough to have personally met Donald Hebb one time. But I hasten to add that I am not so old as to have counted him as a friend. He insisted on it. Let me explain. I was introduced to Professor Hebb just after coming to Dalhousie University as a newly appointed assistant professor in 1984. As I recall, he had an office that he used occasionally in his status as an Emeritus Professor, just inside the main entrance to the Department of Psychology, and not far from a steady flow of student and faculty pedestrian traffic. Richard Brown introduced me as a new hire at Dalhousie, and Professor Hebb, after saying "hello" and a few other pleasantries, leaned in and said, "Please don't be surprised if I don't say hello next time you pass by. At my age, I'm just not in the business of making new friends." "Deal," I said, as I backed out of the door. The comment took me aback at the time, but I have come to respect if for the cogence it highlighted in this aging, and yet deeply self-reflective, scholar and scientist.

The theme of this paper is that *synergy*—or, equivalently, *interaction*—is what makes the science of human perception exciting. I am referring to synergy in at least three different senses when I say this, including statistical interactions in human behavioural data, neural interactions between specialized regions in the brain, and collaborative interactions among research scientists and other scholars.

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Statistical Interactions

Let me begin with statistical interactions. Among all the statistical tests that behavioural researchers have available to them, the one that is still used most frequently is the elegantly simple and straightforward *t* test. It answers a centrally important question for many researchers, namely, "Is there a difference between the outcomes in two conditions?" The *t* test was developed over 100 years ago by William Gosset, a reportedly shy and exceptionally brilliant person who worked for the Guinness Brewing Company in Dublin, Ireland. Gosset developed the test in order to solve the very practical problem of how to come to sound conclusions about *differences* between conditions, especially when the data in each condition were based on relatively small sample sizes. This approach to answering scientific questions by focusing on differences has led to many successes, including the development of a better-tasting pint at Guinness, one we still enjoy today. But the question "Is there a difference?" also has its limits. For example, it is not a very efficient way to answer questions about dynamical or adaptive systems, such as the human nervous system, a system that routinely changes its sensitivity to events and its processing priorities, depending on its recent history and the environment in which it finds itself.

To study that kind of a system, a much more direct test is given by the factorial analysis of variance. And the credit for that achievement goes to Sir Ronald Fisher, a contemporary and friend of William Gosset. Fisher's statistical tool gives a researcher the opportunity to discover a variety of diagnostic interactive patterns in a set of data. Consider, for example, the well-known fully crossed interaction, which shows up as a signature "x" shape on a line graph. Its interpretation is that the influence of one factor on the outcome variable is entirely dependent on values specified by a second factor. In other words, the sensitivity of the system to a stimulus along Dimension A is one way in one context, and completely opposite in another context, where context is defined by the specific values that are tested on the Dimension B.

Another signature or diagnostic pattern that is sometimes seen in a factorial graph of data is a pattern of parallel lines. This signals the existence of a modular or linear system, in which the outcome of the whole (the consequence of two or more variables) is exactly equal to the sum of the parts (the separate consequence of individual dimensions). About 50 years ago, Saul Sternberg (1966) used this framework for pointing to the existence of an internal mental comparison process in short-term visual memory, one that was exhaustive for the number of items to be compared in memory, regardless of whether a match was found (target present trials) or not (target absent trials). Many researchers have used Sternberg's additive-factor analytic tools ever since, in an effort to uncover the hidden workings of the mind.

Having laid out these two starkly contrasting ways in which hidden mental operations can be operating—in a dynamical, context-sensitive way versus as the output of a set of modules that are chained together in series—I hope throughout to be able to appeal to this oversimplified distinction, in order to highlight how the research from my lab has tried to understand the workings of human perception.

My story begins in the early 1980s, around the time when David Hubel (Canadian) and Torsten Wiesel (Norwegian) had been recently recognised with the Nobel Prize. The prize was for their discovery of a class of neurons in the visually sensitive regions of the mammalian brain that were selective to the orientation of an edge of light. Each cell seemed sensitive to a very specific orientation, and only in a very particular region of the eye's retina. After these researchers had gone on to explore the sensitivities of neurons in neighboring regions to these simple edge-detecting neurons, they uncovered the hierarchical processing scheme, illustrated in Figure 1A. At each successive stage, moving from Visual Area 1 (V1) to Area 2 (V2), and so on, the spatial region of sensitivity on the retina grew larger for a given neuron, but at the same time, the geometric property the neuron was sensitive to became more complex (from edges, to angles, to shapes). It was not too large a step from that scheme to the proposal that there must be a grandmother neuron in each brain, meaning a single cell that could respond selectively to a familiar person or object for that brain.

For psychophysical researchers inspired by this revolutionary view of the brain, and I counted myself as one of them in graduate school, it set us on a quest for the behavioural primitives of visual experience. If only we knew what the primitives were, the alphabet of visual experience, so to speak, then surely we would be able to figure out how to combine the elements to make larger shapes,

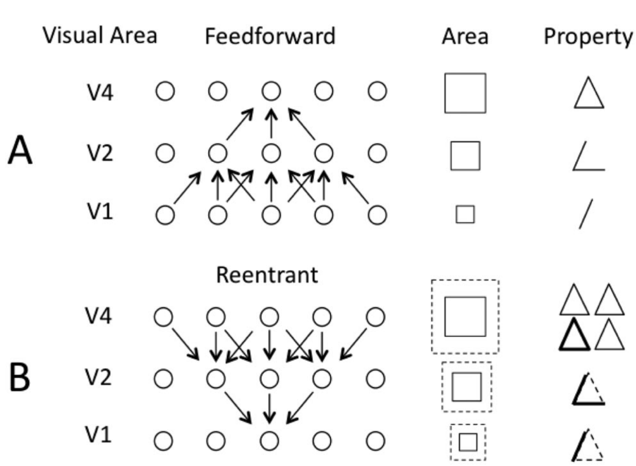

Figure 1. (A) Feedforward signalling in the visual areas of the brain, as proposed by Hubel and Wiesel (1968). (B) Reentrant processing in the same visual areas, as proposed by numerous theorists at the beginning of the 21st century. See text for details.

objects, and perhaps even meaningful visual narratives. Anne Treisman set out in her *Feature Integration Theory* (Treisman & Gelade, 1980) that the primitives of human vision were values along the feature dimensions of orientation (e.g., the values of vertical, tilted, horizontal), hue (e.g., the values of red, green, blue), and motion (e.g., the values of rightward, leftward). The theory proposed that values on these dimensions are initially registered in topographically organized regions of the brain that are separate from one another. In order to identify any particular combination of features as belonging to the same object, information from remote brain regions must be integrated. Such integration requires a master map of spatial locations to which all feature maps have access. Moreover, feature integration is inherently a serial operation; it can only be done one location (or object) at a time.

This theory made clear predictions about the relative difficulty of visual search tasks. Search through a display in which a unique dimensional value defines the target (e.g., a tilted bar among vertical bars) is done quickly and effortlessly, because the tilted target stimulates unique activity in an orientation map that is automatically linked to a master map of visual field locations. In contrast, visual search for a target defined by the spatial relations among two primitive features (e.g., searching for a "T" in a field of "L"s), will be slower and more effortful, because there is no unique activity in the orientation map that distinguishes the two elements. This target must be found by an element-by-element check for the defining spatial relation (a vertical bar meeting a horizontal bar at its centre).

Bela Julesz (1981) made a similar theoretical proposal, but focused on surface texture perception. His quest to catalog the primitives of texture perception led, eventually, to the proposal that a very small class of shape features were primitive, including edge intersection and free edge endings. Julesz called these *textons*, in analogy with protons or gluons. Edge closure and metric spatial relations such as those distinguishing Ts and Ls were decidedly not among the textons of human vision.

This was the fray I jumped into at the end of my graduate school days, with a paper demonstrating that edge closure (the difference between a triangular vs. a trihedral set of lines, and the difference between an "S" and a "10") was effortlessly detectable within a texture under some circumstances, but only detected with effort under other circumstances (Enns, 1986). The experiments showed that the critical circumstances were the other contextual elements in the stimuli, which included the number of features the elements had in common with one another. In short, if edge closure or differences in free edge endings were relatively unique, these features were each effortlessly detectable. If these same features were less unique, because the contrasting stimuli had other features in common, their detectability declined: a classic crossover interaction. Rather than participating as defining features of texture perception, textons were as relative in their consequences as many other familiar dimensions of gradation in human judgment. Even textons were contextually sensitive.

We applied this same tactic, of demonstrating the contextually sensitive nature of visual detection processes, when Ron Rensink (a doctoral-level student in computer science at The University of British Columbia [UBC] at the time) and I tried to apply Triesman's feature integration theory to the perception of the three-dimensional world (Enns & Rensink, 1990a). That paper demonstrated that certain spatial relations between elements popped-out effortlessly in a visual search task, provided that the relations signalled a unique feature value in three-dimensional space. The unique feature value we began with was the direction of lighting in a scene: A target object defined by lighting from below stood out saliently among objects lit from above. And this feature of lighting direction even seemed to have a privileged value, which revealed itself as a search asymmetry: A target object defined by lighting from above did not stand out as saliently among objects lit from below. We proposed that human vision had a default assumption to expect light from above, thereby allowing objects with lighting directions that differed from this default value to stand out. In later papers, Rensink and I used the same methodological tools to explore the detection of an object's orientation in three-dimensional space (Enns & Rensink, 1990b), surface attachment (Aks & Enns, 1996; Enns, 1992), and visual occlusion (Rensink & Enns, 1998).

Indeed, it was in our exploration of occlusion relations (i.e., the perception of objects that are partially obscured by objects nearer to us) that we came to the conclusion that the visual system's bias to see our meager computer displays as consisting of objects in three-dimensional relation to one another did not even allow conscious access to the two-dimensional features we were using to draw the displays. We called this "preemption" (Rensink & Enns, 1995) to emphasise that our experimental results showed that viewers did not even have conscious access to the very elements that Triesman's feature integration theory and Julesz's texton theory predicted were the primitive units of shape and form perception. Instead, viewers performed visual search tasks as though they had the most direct access to the shapes of the three-dimensional objects that were *implied* by the relations of object occlusion. A similar finding was obtained when we tested viewers' ability to search for the line elements in the classic configuration known as the Mueller-Lyer illusion (Rensink & Enns, 1995). Viewers could easily perform search tasks based on the length of the overall configurations of lines, but searching on the basis of the lines that made up the configurations was very difficult.

Neural Interactions

But what was an alternative to this failed class of theories that sought to ground visual perception in an atomistic framework, one in which alphabetic elements could be identified, and then combined into evermore complex entities, in order to explain the perception of meaningful objects? Fortunately, my colleagues and I were not the only ones grappling with this problem. Indeed, the 1990s seemed to foment research findings on many fronts that could not be reconciled with theories that proposed only a feed-forward direction to the stream of neural processes in the brain. Chief among these was the work of Victor Lamme and his group in Amsterdam, who showed that neurons in V1 of the monkey brain did indeed respond to visual activity outside of their classically defined windows on the retina (also known as receptive fields, or regions of retinal excitation). But these researchers also showed that one had to be a little more patient in order to see this activity. For example, when V1 neurons were presented with two identical displays of tilted lines (lines whose orientations were favoured by the activity in those cells), what these tilted lines were surrounded with could make quite a difference (Lamme, Supèr, & Spekreijse, 1998). But critically, this difference only emerged after about the first 1/10 of a second following the display onset. That is, tilted lines in the centre of a neuron's receptive field were responsible for the neuron's activity in the first 100 milliseconds, but after that, the neuron began to behave as though it were part of a larger circuit that understood that it was looking at a shape (as opposed to a background surface). In other words, so-called simple cells were behaving as though they were much more intelligent than the seminal research of Hubel and Wiesel had implied.

The idea that the flow of processing from higher to lower levels in the anatomical hierarchy was as important, if not more important, than the flow of processing from lower to higher levels, soon took hold on many fronts. Shipp and Zeki (1989) traced the connections between retinal information that went to V1 and V5 (a higher order centre important for motion perception) and reported that some of that information made it to V5 even before it got to V1. V5, in turn, sent more signals back to V1 than V1 sent to it, and the spatial pattern was even quite different. These authors speculated that this so-called reentrant signalling (from a higher region to a lower region) might be serving the functions of error correction, anticipatory priming, and signal integration, so that low-level neurons in V1 could be acting in concert with the higher level neurons in V5 to form a coherent circuit that could guide intelligent behaviour in the animal.

Soon there were several highly influential theoretical treatments of the importance of reentrant processing in visual perception, including the theory of "neural Darwinism" by the Nobel Prize winning immunologist Gerald Edelman (1993), a proposal for a brain architecture based on "cortico-cortico loops" by Mumford (1992), "predictive coding theory" by Rao and Ballard (1999), eventually leading to the now well-known "reverse hierarchy theory" of Ahissar and Hochstein (2004), and the popular book treatment of the "brain as a prediction machine" by Hawkins and Blakeslee (2004). These ideas are shown by the reverse flow of neural information through the anatomical processing hierarchy, as illustrated in Figure 1B. The upshot of these ideas is that they encouraged researchers to think of perception as much less of a static enterprise than it had been considered to that point. Instead of having to search for the building blocks of perception in the lowest levels of the neural coding hierarchy, one could now consider how the goals and interests of the viewer might have a direct influence on the way perception might proceed. This way of thinking even promised to make research on the individual differences that we all bring to a perceptual task a little more tractable. These differences would be directly influenced by our unique past experience in a given context, our skills and expertise, and even differences in the way our brains had matured over time. These influences would be reflected in the downward flow of neural information, making the search for a bedrock of neurons or circuitry at the lowest level, which could be counted on to anchor perception, rather moot.

What this way of thinking offered me in a very practical way—as a self-identified psychophysical vision researcher—was a new way to think about one of the oldest enigmas in visual perception, namely, the puzzle of backward masking. "Masking" is a very general term that refers to the deleterious influence of a neighbouring stimulus on a target stimulus. So as a simple example of *spatial* masking, a single letter on a page is easier to read out of the corner of your eye than the same letter when it is surrounded by other letters. The term "backward" in the context of masking refers to a *temporal* effect. A briefly presented target shape is easier to see when it is presented alone than when it is followed shortly after in time by another shape. *Preceding* the target shape with another nontarget shape can make target detection a little more difficult, but detection suffers more by several orders of magnitude when the nontarget shape *follows* the target shape. Thus, it is this backward aspect of masking that is most intriguing. An explanation is needed for the fact that something coming *after* a critical event can influence our perception of that critical event.

There are many varieties of masking in the perception literature, and numerous theories to account for them, but it is fair to say that most of these theories treat backward masking as some kind of a failure or limitation of the visual system. The theories began with the assumption that backward masking is a way of probing the spatial and temporal limitations of vision. As such, spatial masking could be used to point to the inherent limits of spatial resolution over the visual field, temporal masking pointed to the sluggish nature of processing, which allowed a new stimulus to interfere with an earlier one when the earlier one had not been fully processed.

The serendipity of hosting the recently retired Professor Vince Di Lollo in my lab, beginning in the fall of 1995, along with the theoretical preparation of the emerging views on reentrant processing, sowed the seeds for a radical reinterpretation of backward masking. What Vince brought to the lab, in addition to his Italian accent and many scholarly connections to Perth, Winnipeg, and Edmonton, was a curious new form of masking that failed to conform to the standard rules. These rules included the so-called *spatial proximity law* (masking should get stronger as the target and masking shapes got closer to one another) and the so-called *stimulus onset asynchrony law* (masking should be strongest when the onset of the masking shape *followed* the onset of the target shape by the ideal amount of time, usually 50 to 100 ms). The masking effect Vince had stumbled upon involved surrounding a target shape with a meager four dots. Surprisingly, the distance between the dots and the target shape did not seem to matter with this kind of masking, and neither did the temporal rules; the dots could begin their life on the screen at the same time that the target shape was onset without reducing the masking effect. In other words, the stimulus onset asynchrony law was violated as well. The critical factors that did influence this new form of masking, which quickly became known in our hands as *four-dot masking*, was that there had to be some uncertainty prior to the onset of the target about where the mask would appear, and the four dots had to persist on the screen in the rough location of the target after the target shape had disappeared from view (Enns & Di Lollo, 1997, 2000).

The theoretical idea that we took from the new reentrant theories of perception was that backward masking was a byproduct of the visual system's bias—a highly adaptive bias—to perceive a stable world. This bias made it vulnerable to backward masking in the lab, but it was our working idea that, under everyday circumstances, this bias assisted the viewer in maintaining perceptual continuity in the face of the viewer's body movements, head and eye movements, and the occasional movements of objects against the background surfaces of the environment. This bias, when taken into the lab, or indeed when used for the purposes of entertainment by a skilled magician, could lead to the viewer being deceived by a phenomenon we at first called *object substitution* (Enns, 2008; Enns & Di Lollo, 1997), and then later began referring to as *object updating* (Enns, Lleras, & Moore, 2009; Lleras & Enns, 2004; Moore, Mordkoff, & Enns, 2007), in order to expand the concept beyond the narrow confines of visual masking.

Prediction as the Brain's Modus Operandus

Indeed, this notion of object updating soon became critical in helping us understand a surprising finding in the realm of visual search, which few would think of as having much in common with masking. Early in the 2000s, the Nissan Corporation had given my lab some generous funding to help them understand the limitations and possibilities of drivers interacting with the electronic displays that were suddenly appearing in the new automobiles. Nissan's interest lay in helping drivers both use these devices and to do so safely. Their engineers asked us to conduct experiments relevant to the issues of how much of a visual scene is retained by the driver when s/he makes a brief glance away from the road (e.g., to the rear view mirror or to the in-vehicle display).

We began by conducting visual search experiments, which, by then, we already knew how to do quite well, with a new twist (Lleras, Rensink, & Enns, 2005). Occasionally, while participants were searching, the displays would turn off briefly and then reappear, simulating the loss of sensory information that occurs when a viewer glances away from a scene and then back again. We referred to this as an "interrupted search." What surprised us in these experiments was the speed with which correct target detection responses could be made upon the reappearance of the display following the brief interruption. Whereas reliable correct responding began after only 500 ms following the onset of a new search display, correct responses resumed after only 200 ms following the reappearance of a display that had been briefly interrupted. What made this finding even more curious was that these responses did not occur if the display did not reappear. Responding in that case was at chance guessing levels. In other words, these rapid responses were evidence of a form of memory (of the initial glance at the display) that was only reactivated when the expected sensory experience was reinstated (when the interrupted display reappeared). We coined the term *rapid resumption* to refer specifically to these ultrarapid and reliable correct responses that could be made when an expected scene reemerged following brief offset.

Since the time of those initial findings, establishing the existence of the rapid resumption effect, we have gone on to distinguish it from the anticipatory spatial benefits of covert orienting (Lleras & Enns, 2009), from the benefits of foveal over parafoveal vision (van Zoest, Lleras, Kingstone, & Enns, 2007), and we have established that the mental expectation that is formed that allows the rapid resumption of search to occur is one that involves linking an expected visual feature of the target with a motor response that is dependent on that feature (Lleras, Rensink, & Enns, 2007). In other words, viewers are using preliminary visual information from an initial glimpse of the target to predict a subsequent sensory experience and motor activation. This prediction is implicit, in the sense that if the process is interrupted and the participant is consulted about it, they are unable to articulate the prediction with conscious awareness. When we tested young children in search tasks, they, too, showed exactly the same pattern of rapid resumption as adults, despite the fact that they were much slower and less accurate in their ability to search overall (Lleras, Porporino, Burack, & Enns, 2011). Taken together, the data point to implicit, forward-looking, and online predictions being made in the normal course of object perception (Enns & Lleras, 2008). This is consistent with the idea that the human brain is better described fundamentally as a prediction-making device than it is as a seeing or as a remembering device (Hawkins & Blakeslee, 2004).

Most recently, we have conducted new studies premised on this theoretical framework in order to understand why shapes that are in motion seem surprisingly clear to us, despite their smeared registration on our retinas (Lenkic & Enns, 2013). In the realm of cross-modal perception, we have tested the ability of participants to use their haptic sense (active touch) to correctly predict what objects they are seeing (Pesquita et al., 2013), as well as their visual lip-reading ability to predict what words they are hearing (Sánchez-García, Alsius, Enns, & Soto-Faraco, 2011; Sánchez-García, Enns, & Soto-Faraco, 2013). Finally, we have reported new evidence that an object's denotative meaning, as reflected by its familiarity in long-term memory, has an influence on the very edges that are attributed to an object versus the edges that are attributed to a neighbouring shape (Kahan & Enns, 2013). As is evident in the authorship of these articles, the success of this research can be attributed at least as much to the social synergy in the eclectic mix of individuals I have had the pleasure to collaborate with, as it can be attributed to latching on to the right theoretical idea (the importance of reentrant processing) at the right time (as feedforward theoretical models were failing to account for critical findings).

Keeping up With the Times

During the past decade, the fields of research collectively known as the cognitive sciences have shifted once again. Researchers and theorists have, by and large, accepted the reality of the massively reentrant brain, and have taken seriously the idea that the brain is constantly on the prowl making predictions about what will occur next. These predictions range from the most mundane and distant from our awareness (e.g., "What will my hand feel when I grasp the doorknob to enter a room?") to profound questions of our own well-being and social standing that are at the forefront of our awareness (e.g., "How will my response to this event affect my relationship to a partner?"). One consequence of this acceptance is a breaking down of the traditional divisions between the mental content that is considered cognition versus emotion, a breaking down of the division between cognitive and social psychology, and the abandonment of old ideas about which research can be considered labouratory and experimental versus naturalistic and observational. The challenge for a midcareer behavioural researcher like me is whether the tools and techniques I have hanging from my belt are sufficient to be able to advance research in a field that accepts that the subject matter is dynamic—that, for example, a concept such as *attention* must in some circumstances serve as the independent variable (e.g., when attention is distributed vs. focused) and at other times as the dependent variable (e.g., when a certain emotional state such as happiness has an influence on attention, biasing it to be distributed rather than narrowly focused).

My short answer to this challenge is "Of course! Yes, we can." As proof of concept, I will next summarise four different ongoing lines of research from my lab, in each case highlighting how we attempt to deliberately study the dynamics of a given system or feedback loop, rather than ignoring the bidirectional relationship inherent in the system, or treating it as nuisance variance or noise, as was often done in the past. Because many aspects of these projects have not yet made it to peer-reviewed publications, I will apologize in advance if future review shows that some of the data patterns have changed somewhat in going to press. But at the same time, I will offer sufficient peer-reviewed references for the main ideas to defend the general conclusions I offer in each section. I should also point out that the work in each section would not have been possible without the substantial synergy that comes from having scholars with different tools and perspectives join together on a common problem. No one has benefitted from these relationships more than I have.

Action and Value

The individual who has done more than anyone to change the look and feel of my lab over the past 5 years is Craig Chapman. Craig is now an assistant professor at the University of Alberta, but Alan Kingstone and I lured him to our labs at UBC as a jointly funded postdoctoral fellow. What Craig brought was, first, a technical wizardry that allowed us to monitor participants' limbs in action while they performed various tasks, and second, a scientific perspective in which there was no gap between perception and action. As Craig puts it, (C. Chapman, personal communication, May 15, 2013)

> perception is there ultimately to serve action, and the potential for action influences perception from the beginning . . . we need to stop thinking about action as the output of the cognitive process, but rather see it as the observable component of cognition.

He backed this up by developing hardware and software to measure perception and action in tandem (e.g., limb tracking, eye tracking, physiology measurement, immersive displays).

In one project aimed at measuring the influence of an object's value to the participant (Truong, Chapman, Huang, & Enns, 2013), participants were shown all possible pairings of four salty and sugary treats (i.e., Lay's chips, Doritos, Dairy Milk, and Oh Henry!), and simply asked to reach as rapidly as possible to the one they preferred. As an incentive to move rapidly and accurately, they were told that they would leave the experiment with the items they chose on two randomly selected trials.

After performing this task for a few hundred trials, we examined both the kinematics of the reaches participants were making, and, in an exit poll, we asked them to rank the four treats in terms of their preference for them. What we found was a robust relationship between the directness of a participant's reach toward a given item and its rank among their explicitly stated preferences. In other words, we could see their preferences simply by the kinematics of their actions, with stronger preferences leading to more direct reaches. And when we examined the time course of these kinematic telltale signs, it was clear that the strongest signals were to be found in the reaches that were performed most rapidly. This meant that the time course of the decision-making process was evident in the unfolding of the action over time. Inner cognition was directly visible in the observable behaviour of the limb.

We have taken a similar approach in studying how the value of a stimulus exerts its influence in the earliest observable actions made in response to a stimulus (Enns, Chapman, & Gallivan, 2011), and in another example, we have documented how a participant's behaviour in a visual search task, when viewed and rated by a naïve third-party observer, can be used to accurately infer the level of cognitive performance achieved by that participant, even though we never provide the third-party observers with the measures of performance (Brennan, Watson, Kingstone, & Enns, 2011). The everyday expertise we all have in making attributions about others can be harnessed in the service of cognitive psychology. Or, in the wise words often attributed to Yogi Berra, "You can observe a lot by just watching."

But inner cognition is not only reflected to others through observable behaviour. Behaviour of the body itself can have a profound influence on inner cognition. In experiments conducted first with Dan Smilek (then a postdoctoral fellow in the lab) and later with Marcus Watson (a recent PhD graduate of the lab) we studied how instructing participants to adopt certain cognitive strategies in the performance of a task, such as to "simply relax" or to "be as active as possible," had substantial influences on how those tasks were accomplished. For instance, telling participants to relax during a visual search task not only improved the efficiency of search (Smilek, Enns, Eastwood, & Merikle, 2006), but did so by shifting the inherent trading relationship of eye movement behaviour between processing deeply (i.e., fixating or "seeing") and acquiring new information (i.e., saccading or "looking"; Watson, Brennan, Kingstone, & Enns, 2010). In related research, we used techniques of method acting and sympathetic music listening to study how the adoption of a bodily mood state influenced the spatial-temporal consequences of the attentional spotlight (Jefferies, Smilek, Eich, & Enns, 2008).

Looking and Liking

One of my most eclectically skilled collaborators has been Steve DiPaola, from Simon Fraser University's School of Interactive Arts and Design, who is an artist, a performer, and a whiz with computers as they are typically used in the electronic gaming industry. Yet what Steve seems to enjoy most are the difficult scientific questions about how human perception works. One day he walked into my office and asked me to tell him everything I could about how a viewer's eyes might behave when confronted by a new work of art. Specifically, he wanted me to tell him what my field knew about how the eye of a viewer might move in response to a portrait painting by Rembrandt, one in which Rembrandt had rendered one eye in portrait in considerably more detail than he had rendered the other eye. While I hemmed and hawed about what background research in human eye movements might be relevant to this question, Steve started to show me that he had also developed a computer program that could paint, "in the style of Rembrandt," using only a high-resolution photograph as its input (DiPaola, 2009). Always one to seize the opportunity to borrow sophisticated tools developed by others, it dawned on me that the answer to Steve's original question could be answered by the two of us working in tandem. In so doing, we would have the good fortune to be able to test a hypothesis that, so far, had been intractable by studying viewer's gaze patterns when viewing original masterpieces of art.

The reason I had difficulty answering Steve's original question, about the gaze of a viewer when looking at a Rembrandt masterpiece, was that there was no proper control condition. When artists select one region of the canvas to receive a more detailed treatment and another region as receiving less detailed treatment, it is not only the level of detail that differs between the two regions. These regions almost always differ in their spatial position within the larger composition, they differ in their semantic content or meaningfulness to the viewer, and they differ in the implied lighting given to the two regions, among many other variables. This meant that one could do crude correlational studies to address the question using masterpieces, but a proper experiment was out of the question. Steve's Rembrandt-like painting program, however, changed what was possible. If we could use it to create plausible masterpieces (i.e., images that naïve viewers would accept as plausible works of art), then we could compare gaze behaviour to precisely the same region in a painting, once when it was rendered in sharp detail and then again when it was rendered in coarser detail.

We pursued this strategy with some success, demonstrating first that viewers' gaze was indeed attracted to, and held longer, when an eye region in a portrait was rendered in sharper detail (DiPaola, Riebe, & Enns, 2010). In that article, we also found preliminary evidence that Rembrandt's style of selective detail in a portrait could be linked to viewer's preferences for various portraits. All of this suggested to us that Rembrandt might have been among the first of the Renaissance artists to understand (intuitively, or perhaps even explicitly) that there was a direct link between how the eye is guided implicitly in a work of art and how much the viewer appreciates or likes the artwork.

In order to flesh out what we call the detail-gaze hypothesis more completely, we branched out from this research in two directions. One the one hand, we thought it was important to find out whether the eye was driven by relative detail more generally, say, when viewing naturalistic scenes, and on the other hand, we thought it was important to establish a more direct link between the behaviour of the eyes and subjective evaluations of a painting's relative worth.

The work with naturalistic scenes was done with our own collections of photos from social media sites (Enns & MacDonald, 2013a). In each photo, we randomly selected a region, on the right or on the left, for a Photoshop treatment of enhanced clarity or reduced clarity (relative to the background), using the Gaussian Blur tool. These treatments were quite subtle, so that in many cases, participants were unaware that they were looking at a photo that had been tampered with at all. The cover task we gave participants was to study each picture for 5 s in preparation for a new–old recognition test. Our real interest was in whether these regions would attract greater or lesser looking as a function of our treatment. What we found was that even very subtle differences in clarity changed participants' gaze patterns, with more first fixations occurring sooner to regions that were relatively sharp than the same regions when they were blurred. Moreover, this pattern held over a range of different cover tasks, including those that encouraged equal looking to sharp and blurred regions (i.e., because we tested their memory and attributions of the personality of people depicted in these regions). This pattern also held when it was applied to regions that varied widely in their semantic interest to the viewers. That is, over and above the expected findings that viewers looked more often to image regions containing objects of interest, the consequences of selective sharpening and blur for gaze behaviour were observed at all levels of image interest.

It was one thing to show that looking is so profoundly affected by subtle manipulations of clarity and blur; what are the consequences for the subjective evaluation of these images and for the persons depicted in them? To get at this question, we have now conducted studies examining how personal attributions to people are influenced by subtle manipulations of clarity and blur (Enns & MacDonald, 2013b). The main finding is that people seem to be as unable to discount superficial image characteristics when subjectively evaluating people in photos as they are unable to discount structural physiognomy (Oosterhof & Todorov, 2008). In both cases, humans make unwarranted inverse inferences, which, for image clarity and blur, run along the lines of "Sociable people tend to be self-revealing. I can see someone in a picture more clearly, therefore they must be socially outgoing."

We have also conducted more detailed analyses of the links between looking selectively at one of two eyes in a set of portraits and the consequences for how well-liked the portraits are when rated relative to one another (DiPaola, Riebe, & Enns, 2013). These analyses clearly imply that viewers rate a portrait more positively when their own eyes dwell longer on one of the two eyes in the portrait. It is as though viewers can implicitly feel that the artist has a plan for their gaze, and when that plan is clearly laid out, using the techniques of relative detail and painterly highlighting, then viewers respond with a greater appreciation of the portrait.

Learning and Conscious Experience

One of my recently completed graduate students, Marcus Watson, seduced me into a research program of studying the human condition known as *synesthesia*, that rare and seemingly harmless phenomenon some people experience, involving a secondary sensation in response to a trigger sensation, usually in an unrelated modality. For example, colour-grapheme synesthetes experience the usual black letters that most of us see on the printed page in a rich range of hues. The standard way they prove this to a researcher is by being able to reliably identify the hue of each letter shape when asked. From the beginning, I was reluctant to get involved in this topic, often badgering Marcus to come up with a good reason why cognitive scientists should be concerned with this private phenomenon. Over time, he won me over, by demonstrating that colour-grapheme synesthesia was a perfect microcosm for studying the dynamic relations that can occur between learning and conscious experience.

Learning is clearly involved in colour-grapheme synesthesia, even though these individuals may be born with special brains or neural wiring that differs from the norm. That is because the letters of the alphabet are a culturally learned set of symbols, typically learned during the first 5 to 7 years of life. Had these individuals been exposed to a different language, other shapes and associations would have been involved. So at least the triggering sensation has a critical learning component. The conscious experience is remarkably tractable in synesthesia, in a way that other conscious experiences are not, principally because the human gamut of hue experience is well understood and we have precise ways of measuring it. So two critical elements were in place to study the learning–experience loop.

Marcus has now developed his thinking about this loop sufficiently to be able to articulate three tractable hypotheses. First, synesthetic concurrent experiences (i.e., seeing colour in a physically black letter) are, to some extent, a consequence of being faced with a learning challenge (i.e., learning the letters of the alphabet by shape). Whether all or only some children have the capability of facing the challenge this way is still not known, but the data we have collected from a large scale epidemiological study of synesthesia in two countries (a total sample size of nearly 12,000 participants in Canada and the Czech Republic) indicates that the incidence of synesthesia can be directly linked to the challenge of learning the orthography of a second language. That is, whereas the incidence of synesthesia is around 1% in the population for people who learn two or more languages from birth, it rises to over 3% when people are faced with learning to read a second language in the period of 5 to 10 years of age (Watson et al., 2013).

A second hypothesis is that the mapping of colours to letters is not arbitrary, but is *information preserving*. By this we mean that the assignment of colours to letters is accomplished to assist discrimination of the shapes that are being learned. Whether this aspect of the assignment is consciously accessible to participants is also not yet well understood, but there are several ways in which we now know the assignment serves this purpose. Both in an existing sample of 54 synesthetes in Canada, as well as in two other samples that are much larger, one of them in the Czech Republic, the assignment of colours to letters has been shown to assist the discrimination of shape (i.e., similar shapes receive similar hue assignments), the preservation of letter order in the alphabet (i.e., letters earlier in the alphabet have more distinct hues), and tracking the frequency of letter occurrence (i.e., more frequently occurring letters are brighter; Watson, Akins, & Enns, 2011, 2012).

Although we have not yet shown that these information-preserving mappings are useful to young synesthetes when they are learning to read, we have shown that synaesthetic experiences can be exploited when learning new material. To do this, we designed a difficult trial-and-error category-learning task that was custom tailored to each synesthete in the study (Watson, Blair, Kozik, Akins, & Enns, 2012). If the task was accomplished using only letter shape, it was a very difficult task with a slow learning curve. However, if the task was accomplished using the associated letter colours, it became quite easy. To see how the synesthetes solved the task, we compared their learning results with two groups of nonsynesthete controls: one group looking only at black letters, and one group looking at letters coloured in the same way as reported by the synesthetes. The results were clear. Synesthetes spontaneously used their colour experiences to make the task as easy as the control participants viewing physically coloured letters.

Our goal now is to show that that these three hypotheses are causally linked, that is, to demonstrate that the information preserving aspect of the colour mapping (the second hypothesis above) is a consequence of the learning challenge (the first hypothesis), and so on. But this is work for the future. For now we are gratified that all components of the loop in the learning–experience dynamical system are in place.

Social Signals and Perception

As a final example of work in progress, let me describe how we are currently studying the dynamic relationships between perception and social collaboration. In one series of studies, we are measuring the sensitivity of humans to the quality of social interactions they are observing, so we are looking at the *perception of* social relations. In another series, we are manipulating the social setting in which perception occurs, in order to examine the conditions under which two heads can see better than only one head. There the focus is on how social relations *influence perception*.

To study the perception of social interactions, we are using the microcosm of improvised jazz duets (Enns, Pesquita, & Corlis, 2012). To create our stimulus materials, we have invited (and paid) first-rate professional jazz musicians to come to the lab to make some playful and engaging recordings of songs they play professionally on a regular basis. These include the New Orleans jazz standards of “Take the A Train,” “Beautiful Love,” and “Canal Street Blues.” The musicians can hear a click-track while they play the pieces, allowing us to maintain a certain uniformity on the tempo of a song that they play for us several times, but each time in a somewhat different way, depending on how they respond to each other on that occasion. Each musician is in a separate soundproof booth, allowing them to hear one another through a live feed into their earpieces, but also allowing us to make separate recordings of each instrument.

We then used these recordings to construct the following three types of duets. The condition we were most interested in, of course, was the one with live duets, which allowed for two-way auditory interactions to occur between the performers. These live duets were compared with dubbed duets, where one musician played along with a prerecorded track of the other musician from a previous recording, without knowledge that the other musician was not live at the moment. The live duets were also compared with studio-mix duets, which involved separate live recordings of each musician that were combined in the studio by taking a portion of the same song, played by each instrument on a separate occasion.

Participants listened to these duets in a random order and, in one experiment, made an explicit judgment of whether or not they were live recordings. In another experiment, a different group of participants rated the recordings on four dimensions of musicality, including emotionality, engagement, creativity, and synergy. Participants in both experiments were also categorised according to their social aptitude (Autism Spectrum Quotient) and according to their musical training (Musical Expertise Questionnaire). The results showed that many listeners were sensitive to social collaboration in this setting of improvised jazz, and that among listeners’ with the least musical training, this sensitivity was linked to their social aptitude. In other words, social intelligence helps listeners to understand jazz, even though they are unfamiliar with the genre.

These findings demonstrate that the human ability to assess the quality of a social interaction (Decety & Jackson, 2006) is present even when the interaction is auditory, nonverbal, and in a medium in which the listeners themselves are not skilled. They also imply an important link between social skill and the ability to perceive the quality of a social interaction in music (Phillips-Silver & Keller, 2012). In the most recent study we have conducted in this series, we asked participants to simply tap to the beat of the music (Pesquita, Corlis, & Enns, 2013). Here, the results show that the variability in tapping is also linked to the degree to which there is the possibility of social interaction in the recorded music. We summarise this finding by saying “even the body can tell” when that intangible synergy of social collaboration adds value to the music we are listening to.

My graduate student Allison Brennan is someone who knows, first hand, the benefits of social sharing in task performance. This is because in her life prior to graduate school, she was an elite collegiate rower who helped her university’s four-women crew win a national title in the United States. In graduate school, she has turned her attention to the question of when can two people work together on a visual cognitive task such that their joint performance is better than the mere statistical benefit one would expect from processing redundant signals (Miller, 1982). In other words, Allison is interested in quantifying the synergy that sometimes occurs when two people join forces, working together in such a way that their joint performance exceeds the sum of their individual efforts.

To do this, Allison gives individuals and pairs of individuals the task of trying to determine, quickly and accurately, how many targets are present in a naturalistic visual search display that may have zero, one, or two of four possible targets in it. We think of this task as a labouratory proxy for the everyday tasks that many of us perform together with partners, including that of navigating while driving in a new city, searching a Web site together for new information on a topic of mutual interest, and looking for a friend arriving at the airport.

The mathematical tools developed previously by Jeff Miller to study how a single brain can benefit from a redundant visual or audiovisual signal (Miller, 1982; Ulrich, Miller, & Schröter, 2007) have been very helpful in this project. These tools have essentially allowed us to treat two people as redundant signal processors in the context of a social system. What we have found so far is that there are at least two separate kinds of factors that influence the extent of social collaboration in joint task performance (Brennan & Enns, 2013). One factor is the degree of existing friendship present among the cooperating partners. We measure this with both self-report measures and third-person observation of the videos from the joint testing session. A second, independent factor is the degree to which the verbal communication between the two partners in the testing session is similar in quantity. Together, these two factors account for more than 50% of the variance between the performances of 22 pairs of partners working jointly on the visual search task. Admittedly, we are only scratching the surface of this intriguing relationship between perception and social collaboration, but these early findings are encouraging us to think even more broadly at the possible bidirectional connections between our relationships in the social realm and the ability of our individual brains to process information.

Conclusion

From my perspective, of having spent more than 30 years researching that elusive topic we call human perception, there has never been a more exciting and promising time than the present. In large part, I believe this is true because my favoured field of research has fully embraced the importance of *synergy* in all three of the senses I have spoken about. First, it is rare these days that the discovery of a simple difference in perception moves the field forward. Instead, progress is made when these differences are contextualized, meaning that their interaction with more than one experimental factor is explored. Increasingly, these other factors include factors that are endogenous to an individual (i.e., their goals, their mood, their past history) and those that are exogenous (i.e., the environmental conditions, the social setting). This is helping to close the gap between labouratory and life in understanding human perception.

Second, theories that ignore the ubiquitous reentrant properties of neural signalling also seem to have little chance of moving the field forward. We can no longer afford to ignore the inherently dynamic nature of the brain, either because it makes our work more complicated, or because it is a nuisance to our parsimonious feedforward theories. I argue that the greatest progress has been made when the dynamical nature of the brain has been studied directly. The research I have summarised is a demonstration that taking reentrant processes seriously changes the very questions and hypotheses we pursue. Taking this approach has also helped to narrow the divide between the fields traditionally known as perception, cognition, emotion, and social psychology.

Third, in my opinion, I have made my most interesting discoveries when I have teamed up with scientists and scholars who knew things I did not know and could do things that I could not do. People outside my field tend to look at the world differently than I do; listening to their questions helped me move in directions I would have not considered on my own. Although the theoretical ground will almost certainly shift as much in the next 30 years as it has in the past 30 years, I am confident that great progress will be made if we continue to conduct research that benefits from, and is informed by, each of these three different types of synergy.

Résumé

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Mots-clés : attention, perception visuelle, action, émotion, collaboration sociale.

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