Action and Attention[1]

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Historical Context

At the very beginnings of the scientific study of psychology in North America, scholars were considering the structure of human actions and the nature of attention as topics of investigation. They were, however, considering them independently of each other. In Principles of Psychology (1890), William James categorized the varieties of attention into three dichotomies: sensorial or intellectual, immediate or derived, and passive (reflexive) or active (voluntary). These dichotomies continue to resonate in attentional research to this day. Not a full decade later, in 1899, Robert Woodworth, who once studied with James, completed his PhD at Columbia University with a thesis entitled "Accuracy of Voluntary Movement". This work set the stage for the modern psychological study of action, and many of Woodworth's initial insights remain valid to this day. Contemporary with James and Woodworth, a possible mechanism for connecting attention and action was proposed by John Dewey (1896) with his "coördination" of sensory and motor processes. In seeking a unifying principle for the fledgling discipline of psychology, Dewey dismissed the notion of a reflex arc - where sensation and action are viewed as the starting point (stimulus) and the end point (response) of a series of disjointed processes of human behaviour. Rather, he promoted an uninterrupted cycle of sensori-motor processing as the appropriate framework for understanding human behavior. Accordingly, attention is seen as a key "central process" in guiding the flow of sensorimotor coordination.

By the turn of the 20th century, the trail heads were in place for the scientific exploration of the human attention system, the human action system, and the interactions of the two systems. John Watson's (1913) "Psychology as the Behaviourist Views It", however,

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set a different path for psychology in North America, and Behaviourism would dominate the experimental psychology landscape for the next three decades. The concept of attention, like any other mental construct, simply did not fit within the behaviourist paradigm. The first Hixon Symposium on "Cerebral Mechanisms of Behavior", in 1948, heralded the rise of cognitive science, and with it cognitive psychology. But in the framework of information processing, actions were typically studied in the absence of attentional manipulations (e.g., Paul Fitts's seminal work on speed-accuracy trade-offs; 1954) and attention was typically studied in the absence of actions (e.g., Cherry's often cited "cocktail party effect" of attentional selection; 1953). Across six decades of research, this separation remains prevalent to this day.

There is, however, an important and ever growing recognition that viewing attention and action in isolation will not offer a realistic representation of either of the two types of processes. In the 1980s, Alan Allport (e.g., Allport, 1980; 1987) argued that cognitive psychology would be best advanced by treating the brain and behaviour as its subject-matter, instead of an over-interpreted computer metaphor (Driver, 2001). In making his case, Allport pointed out that selection is a key component in both perception and action, and what is selected in one system will ultimately influence what is selected in the other system. While several researchers also made this connection (e.g., Keele & Neill, 1978; Marcel, 1983; Shallice, 1972), Allport (1987) was the first to articulate the notion of "selection-for-action", with the selectivity of the attention system playing a critical role in the planning and control of actions. Coming from a similar neurological starting point, Rizzolatti and his colleagues introduced the premotor theory of attention in 1987. This model completely did away with the separation between attention and actions systems and instead hypothesized that the control of attention is drawn from the same neural circuits that are used to control eye movements. Thus, by the end of the 1980s, connections between attention and action had become established enough to essentially form a new subfield of investigation (c.f., Allport, 1989; Neumann, 1990).

The Premotor Theory of Attention

The premotor theory of attention married action and attention by refuting the prominent idea that attention was functionally and anatomically distinct from the systems that control eye movements. Furthermore, it rejected the assumption that attention was a mental operation upon passively received information. In this account, covert shifts of attention (that is, shifts of attention without accompanying eye movements) are essentially planned, but unexecuted saccades. To support this theory, Rizzolatti and colleagues (1987) demonstrated the meridian effect, which showed that orienting of attention obeys the anatomical constraints of eye movements. The basic finding was that shifting attention between hemifields was more costly than shifting attention equidistantly within a hemifield. This meridian effect is easily explained by a theory that assumes the orienting of attention involves the preparation of eye movements: moving the eyes to an unexpected location within a hemifield requires reprogramming of the saccade amplitude, but not direction; making a saccade to the contralateral hemifield requires a new motor program altogether. This additional recalculation takes time. Although the eyes did not move in their study, the meridian effect demonstrates that shifts of attention obey the anatomical constraints of eye movements, supporting a premotor theory of attentional shifts.

If the orienting of attention is indeed yoked to the movement of the eyes, then it follows that wherever the endpoint location of a planned saccade is, attention should precede the eye to that same endpoint location. In support of this prediction, preparing a saccade to a region in space increased the efficiency of target detection at that location (Hoffman & Subramanian, 1995). Likewise, priming from a peripheral object that appears prior to a saccade is only effective when the prime appears at the terminal saccade location (Godijn & Pratt, 2002). These results suggest that preparing a saccade moves attention to the terminal location of the saccade. In a similar study, Deubel & Schneider (1996) showed that it is not possible to direct attention to one location while saccading to another nearby location, indicating a strong, obligatory coupling between saccade preparation and the orienting of attention. The premotor theory of attention predicts that this effect should be reciprocal: Preparing eye movements shifts attention, and shifting attention should assist the preparation of eye movements. Indeed, shifting attention to a peripheral location makes saccades to that location faster and more accurate (Kowler, Anderson, Dosher, & Blaser, 1995). In a similar study, covertly orienting attention altered the trajectories of concurrent saccades, suggesting that the orienting of attention necessarily activates oculomotor circuits (Sheliga, Riggio, & Rizzolatti, 1994; Sheliga, Riggio, & Rizzolatti, 1995). Further corroborating this line of research is evidence that perceptual sensitivity is enhanced to targets likely to appear at attended locations; planning eye movements prepares the observer for perception at that location (Kingstone & Klein, 1991; Hoffmann & Kunde, 1999). Together, these studies demonstrate the reciprocal relationship between orienting attention and eye movements.

If the orienting of attention is necessarily preceded by covert oculomotor preparation, as the premotor theory of attention suggests, then limiting eye movements should also limit the orienting of attention. To test this assertion, Craighero and colleagues had participants perform a classic spatial cueing paradigm (Posner, 1980) with the display positioned 40° to the left or right of the participant's head. This unorthodox positioning of the display meant that participants had to move their eyes to their rotational limit within the orbits in order to fixate on the display's centre; they could not move their eyes any further in the temporal direction, although they could move their eyes in the nasal direction. A typical cueing effect was found on the nasal side of the display, indicating that attention was free to orient in that direction. By contrast, there was no difference between validly and invalidly cued targets on the temporal side, where eye movements were limited (Craighero, Nascimben, & Fadiga, 2004). A similar study had participants with VI cranial nerve palsy perform the typical spatial cueing paradigm under monocular conditions (Craighero, Carta, & Fadiga, 2001). In their healthy eye, these patients oriented attention normally, showing a delayed detection of invalidly cued targets. In contrast, performing the task with their paretic eye revealed no difference between validly and invalidly cued targets, indicating they did not orient toward the cue. These findings support the idea that orienting of attention depends on the ability to plan and execute eye movements. Interestingly, even congenitally blind individuals demonstrate the link between eye movement preparation and attention. When attention is directed peripherally by an auditory cue, these individuals showed a robust activation in the oculomotor circuit under fMRI (specifically, the frontal eye fields; Garg, Schwartz, & Stevens, 2007). Critically, this pattern of activation was also demonstrated in sighted controls.

Action-Based Attention

The premotor theory of attention holds that the control of attention is inextricably linked to the preparation of eye movements. However, eye movements are not the only type of actions that might influence selective attention. A critical step to connect selective attention to manual actions was taken by Tipper, Lortie, & Bayliss (1992), who argued that attention uses an action-centered representation during reaching. In their task, participants reached for a target on a three-by-three array. Critically, a distractor would appear simultaneously at another location with target onset. Results showed a delayed response time when the distractor was in the reach trajectory, compared to when the distractor was outside the reach trajectory. This result prompted the conclusion that attention is distributed within an action-centered representation during reaching, as interference from the distractors was greatest when they were obstacles to the reaching action. Performing a reaching action changed what stimuli were processed, with the reaching-relevant distractors receiving priority over the reaching-irrelevant distractors. An important extension to these results was reported in a reaching task where a physical obstacle would sometimes impede the reaching action. The obstacle's location would presumably be removed from the representation of the action-relevant space. Consistent with this notion, a visual distractor along the reach trajectory interfered less with the action when the physical obstacle was present (Meegan & Tipper, 1999).

The processing cost of a distractor along the path of reaching action is indicative of an inhibited action plan. This idea is supported by research using a similar selective reaching task with older adults and patients with Alzheimer's disease, who suffer from a dramatic loss in the ability to use inhibitory processes (Simone & Baylis, 1997). In this study, older healthy adults showed similar patterns of distractor interference to that found by Tipper et al. (1992). Alzheimer's patients, however, showed greatly enlarged interference effects, despite being able to discriminate the distractors from the targets. It is worth noting that the frame of reference for action-based attention may change with age, as Bloesch, Davoli, and Abrams (2013) found that healthy older adults used a body-centred frame of reference while younger adults used the hand-centered frame reported by Tipper et al. (1992).

To further investigate the nature of action-centered representations of action, Pratt & Abrams (1994) used a similar selective reaching paradigm to pinpoint the submovements of reaching that are affected by action-relevant distractors. They had participants move a cursor from a start position to a target appearing in one of three boxes along a single path. On some trials, a distractor could appear at one of the empty locations adjacent to the target. They found that distractors in the path of the cursor delayed response times compared to distractors on the other side of the target, replicating Tipper et al. (1992). They also recorded the time from target onset to movement onset, the time from movement onset to peak velocity (ballistic phase), and the time from peak velocity to the end of the movement (corrective phase). They found that distractors on the path of the reaching action prolonged movement onset and the corrective phase, suggesting that action-centered inhibition affects both the planning and the execution of reaching actions. This result is in agreement with other work showing that distractors that appear in the action-relevant space interfere with reaching responses during both movement preparation and execution (Meegan & Tipper, 1998). These studies show that the planning and execution of action shapes selective attention through action-centered representation of space.

The notion of action-based attention received further support by studies showing that the transport kinematics of a reaching action deflect away from non-targets near the hand in a cluttered environment, further supporting the notion that attention uses an action-centered representation during reaching (Tipper, Howard, & Jackson, 1997). However, other studies have shown that reaching trajectories may veer *toward* distractors in a selective reaching task (Welsh, Elliott, & Weeks, 1999). While these studies agree that reaching-relevant distractors are automatically processed, the patterns of data seem in conflict. The response activation model of selective reaching can explain these seemingly contradictory results: When a distracting stimulus is presented sufficiently in advance of the reaching target (~-750ms), its representation is inhibited and the movement trajectory deflects away from the distractor's location; when the distracting stimulus is presented closer to target presentation (-250ms – 0ms), there is insufficient time to inhibit its representation, resulting in a deflection toward the distractor (Welsh & Elliott, 2004; see Howard & Tipper, 1997 for an alternative explanation).

The premotor theory was initially conceived as a link between oculomotor activity and attention. However, paradigms designed to examine the link between eye movements and attentional orienting have been repurposed to show that the allocation of attention is linked to manual motor activity as well. Earlier, we described a study by Deubel & Schneider (1996), who asked participants to prepare a saccade while performing a visual discrimination task at different locations. They found that performance was best when the target appeared at the programmed saccade destination. Deubel, Schneider, and Paprotta (1998) adapted this oculomotor paradigm for guided limb movements. Participants were instructed to prepare a reaching movement to a specific location while also identifying a target embedded among distractors. During the preparation phase of the limb movement, the target was very briefly unmasked, Identification of this target was best when the limb movement was planned to the same location. Further extensions of this paradigm have tested whether attention can be simultaneously allocated to up to two or three action-relevant locations in the scene. In particular, when subjects plan multiple sequential eye movements (Baldauf & Deubel, 2008a), sequential reach movements (Baldauf & Deubel, 2009; Baldauf, Wolf, & Deubel, 2006), or bimanual grasps (Schiegg, Deubel, & Schneider, 2003, Baldauf & Deubel, 2008b), visual selection is enhanced for all of the action-relevant locations (Baldauf & Deubel, 2010).

These studies demonstrate that an action-attention link pervades human movement; wherever actions are directed, attention moves as well.

One corollary of the view that attention uses action-centered representations of space is that the information selected by attention during action should depend on the action being performed. To investigate this claim, Welsh and Pratt (2008) had participants detect stimuli using either a point-and-reach or a simple keypress response. On every trial, the participants knew to look for either an onset or an offset. Critically, on some trials, the target would be presented simultaneously with a distractor that would be the opposite stimulus (i.e. if the target was an onset, the distractor would be an offset or vice versa). The question was whether distractor cost would depend on response type, akin to how a perceptual goal can determine the cost of an irrelevant distractor (Folk, Remington, & Johnston, 1992). Results showed that when making keypress responses, both onset and offset distractors captured attention. This is consistent with the informational demands of the action, as keypress actions are indifferent to the presence or absence of stimulation. In contrast, point-and-reach responses are sensitive to information that remains present throughout the action in order to facilitate the online guidance of action. Consequently, transient onsets captured attention, because they introduce new information, but offsets did not. By demonstrating that the type of action being performed determines the type of events that can capture attention depends on the action, action systems can be viewed as a potential source of attentional control setting. Thus, the line of research beginning with Tipper et al. (1992) revealed how information that is potentially relevant to successful control of action influences selective attention. In the example of reaching, this means a higher selective benefit for new objects that appear on display, compared with those that disappear (Welsh & Pratt, 2008), and higher selective benefit for objects that appear along the reaching trajectory, compared with those that appear outside the trajectory (Festman, Adam, Pratt, & Fischer, 2013). After establishing the sensitivity of attentional processing to action-based spatial representation, the question becomes whether this attentional sensitivity is limited to the mere presence of objects in space or whether it extends to selection across other perceptual dimensions.

Actions and Feature-based Attention

To investigate the role of actions on attention further, it is useful to compare attentional processes across modes of actions that target different perceptual dimensions. Compared with reaching movements, grasping an object makes a different subset of available visual information pertinent. For example, the object's orientation becomes critical in constraining hand orientation and the object's size becomes critical in determining grip aperture. Indeed, evidence suggests that attention to both orientation and size is enhanced when observers are in grasping mode compared to when they are in reaching mode. Bekkering and Neggers (2002) employed a visual search task in which a target was defined based on orientation-color feature conjunction. The authors varied the type of action performed toward the target (reaching vs. grasping), and compared the number of error saccades toward distractor features. Critically, they found that in the grasping condition the number of saccades toward the non-target orientation was lower compared with the reaching condition. The number of error saccades toward the non-target color, however, did not differ across the two action types. Thus, the intent to perform a reach or grasp altered the efficiency of selecting the action-relevant feature (i.e., orientation).

Grasping has also been shown to enhance attention for size. Wykowska, Schubö, and Hommel (2009) used a dual task, which involved (a) preparing an action (reach vs. grasp), (b) performing a visual search on a separate display, and (c) performing the prepared action. Findings showed that preparing a grasp facilitates visual search for a size singleton, compared to reaching. By contrast, visual search for luminance singleton benefited from preparing to reach. Both findings of Bekkering and Neggers (2002) and Wykowska et al. (2009) demonstrate how adopting an action mode enhances processing the dimensions that are relevant for successful performance of that action. Interestingly, however, this means that performing grasp movements under divided attention allows relevant dimensions of an irrelevant distractor to affect performance. Castiello and colleagues (Bonfiglioni & Castiello, 1998; Castiello, 1996; Kritikos, Bennett, Dunai, & Castiello, 2000) demonstrated that if subject grasp a target while visually keeping track of a distractor object (e.g., counting how many times it was illuminated), features of the distractor object (e.g., its size) influence properties of the action (e.g., grasp aperture).

In addition to enhanced selection of action-relevant dimensions, specific action features can facilitate selection of specific visual features congruent with the action. In a change blindness task, Symes et al. (2008) used fruits and vegetables of small (strawberry) or big (apple) size. They found that detection of small targets was facilitated when participants responded with a precision pinch grasp, whereas detection of big targets was facilitated when responses were made with a whole-hand power grasp. Similarly, Ellis and Tucker (2000) found that seeing an irrelevant object that matched the grip size resulted in faster response execution compared to the mismatch condition. Therefore, the type of action one intends (e.g., grasp vs. reach) and the features of that action (e.g., big vs. small grasp) constrains attentional selection in the perceptual domain.

Ideomotor Theory of Action

In addition to the selective advantage for action-relevant features (e.g., size and orientation in grasping), there is yet another way in which actions can influence attention. This class of action-based effects emerge out of the very nature of cognitive representation of actions. In line with Dewey's (1896) insight, there is little difference between action and perception in the terms of their representation, but that the real difference is in the functional role those representations play (Hommel et al., 2001; Prinz, 1997). This assumption is expressed in the ideomotor theory of action, in its claim that actions are represented in terms of their known perceptual effects (James, 1890; for reviews, see Shin et al., 2010; Stock & Stock, 2004). Consequently, the representation of action-effect activates the motor pattern, which in turn brings about the anticipated perceptual action-effects. The ideomotor theory has been supported by both behavioural (e.g., Elsner & Hommel, 2001; Kunde, 2001) and imaging studies (e.g., Kühn, et al. 2010; Melcher et al., 2008; 2013).

Assuming that actions are accompanied by a set of perceptual anticipations, it follows that perceptual events will be treated differently due to the anticipations that accompany actions (cf., O'Regan & Noë, 2001).

In a demonstration of how anticipated action-effects can be a source of bias, Hommel (1993), employed a variant of a Simon task (Simon, 1990), in which participants responded to a tone pitch by switching on one of two peripheral lights. The two lights were contralaterally assigned to two keys (e.g., the right key switched on the left light). When participants used lights to respond to auditory stimuli coming from the left or right periphery, a Simon compatibility effect was found between the location of the auditory target and the location of the action-effect, inverting the typical Simon effect between key locations and stimuli. In other words, anticipating the action-effect (i.e., switching on the light) eliminated the effect of the spatial relationship between manual keypress and the target. Similarly, Hommel (2004) eliminated the Stroop effect in a condition where participants' own keypress produced a color patch, suggesting that the knowledge of action-effect reduced attentional allocation to the interfering stimulus dimension.

Due to the perceptual nature of action representation, actions can also interfere with perception when there is a similarity between the two types of events. Müsseler and colleagues (Müsseler & Hommel, 1997a; 1997b; Müsseler, Wühr, & Prinz, 2000; Wühr & Müsseler, 2001) found that planning a localized response reduces perceptual identification of a compatible spatial stimulus. For instance, while planning to press the 'left' key, participants' accuracy of detecting a leftward arrow is reduced when compared to a rightward arrow. Kunde and Wühr (2004) generalized these findings by reporting similar interference effects with other forms of action-percept similarity. For instance, planning a vocal response such as "left" and "blue" could, respectively, interfere with perceptual identification of the word 'LEFT' and a blue color patch. This class of findings have been referred to as *action-induced blindness*, highlighting the fact that action planning can have a significant impact on visual cognition.

Recently, Gozli and Pratt (2011) examined a consequence of action-induced blindness in attention, by examining the effect of prepared actions on attentional prioritization of abrupt motion signals. Abrupt motion is one of the strongest sources of attentional capture (Abrams & Christ, 2003), and has been shown to resist top-down goal setting (Al-Aidroos, Guo, & Pratt, 2010). Participants in the Gozli and Pratt (2011) study performed a visual search using manual movements along either the horizontal or the vertical axis. The search display on each trial was preceded by uninformative motion signals along the same or different axis as the response axis. Although both types of motions were prioritized compared with static locations, higher attentional priority was given to stimuli that differed from the prepared response. Consistent with action-induced blindness, motion signals along the same axis as the participants' action received reduced attentional priority.

Early explanations of action-induced blindness (Müsseler & Hommel, 1997a; 1997b) were based on inhibition of the action features (MacKay, 1986). According to this account, features associated with an action plan are temporarily inhibited in order to prevent re-activation of action in stimulus-driven manner. Later explanations of action-induced blindness, however, are based on the idea of code occupation (Hommel et al., 2001). The code occupation, introduced in the Theory of Event Coding (TEC; Hommel et al., 2001; Stoet & Hommel, 1999), assumes that the action features are activated during preparation but they are bound to other action features to form a unified action event. Consistent with the code occupation account, Gozli and Pratt (2011) found that action-induced blindness was eliminated by the congruency between the location of the motion signal and action direction. This form of congruency should not influence a suppression-driven blindness to motion stimuli. By contrast, an interference that is driven by code occupation and separability of the events should be sensitive to the congruency among event features.

The code occupation account further assumes that the feature integration phase is enveloped by a larger time window in which features that have above-baseline activation but are not yet bound. This assumption was supported by Hommel and Schneider (2002), who presented their participants with two consecutive stimuli, the first of which required a localized response, while the second required an identification response. Critically, the identification stimulus was presented early enough that it could reasonably coincide with the pre-selective action processes, in which action codes are activated but not yet integrated. Hommel and Schneider found that compatibility facilitated identification, which is again inconsistent with an inhibition account of action-induced effects and supports the code occupation assumption of the TEC (cf., Müsseler et al., 2005). In order to induce response activation without response selection, Gozli, Goodhew, Moskowitz, & Pratt (2013c) employed uninformative spatial primes (left vs. right). Critically, each response had an acquired action effect (red vs. green). The authors found that the response primes, in addition to biasing response selection, also increased sensitivity to the color associated with the primed response. In short, these results are in line with an account of action planning in which feature activation is followed by feature integration. It seems likely that the feature activation phase increases attentional bias for action features, while feature-integration phase interferes with selection of action-congruent features (Stoet & Hommel, 1999).

The scope of research on actions and attention is drastically expanded when we consider actions as building blocks of higher cognition (Barsalou, 2008; Gallese & Lakoff, 2005). For instance, concepts referring to manual actions (e.g., "push", "pull") are thought to engage the motor system (Glenberg & Kaschak, 2002), and processing concepts that are associated with a location in space (e.g., "bird", "sky") is thought to engage the oculomotor system (Dudschig et al., 2013; Estes et al., 2008; Gozli et al., 2013b). In short, concepts do not only refer to objects and states of affair, but to patterns of bodily activity (Gallese & Lakoff, 2005). Viewing conceptual understanding as involving sensorimotor tendencies enables us to make specific predictions regarding the way concepts can shape attention. Indeed, tracking the time-course of the interaction between concepts and visual attention, Gozli, Chasteen, and Pratt (2013a) found that implied spatial meaning of words interferes with visual attention briefly after the word onset, whereas after some delay processing is facilitated at the compatible location. The same time-course of interaction has been found between language processing and selection of manual actions (Boulenger et al., 2006; Sato et al., 2008). This time-course resembles the action-induced modulations of visual processing and could be explained with the same theoretical assumptions (Hommel et al., 2001).

In summary, the empirical evidence clearly points toward the continuity of mental operations, and against both the separation of processing *modules* (Anderson, 2010; Barsalou, 2008) and the separation of processing *stages* (Spivey & Dale, 2006). Indeed, in the present framework, a clear distinction between attentional priority and action priority seems implausible (Baldauf & Deubel, 2010; Bisley & Goldberg, 2010; Fecteau & Munoz, 2006). Processes that are referred to as 'action selection' seem to parallel those that control allocation of attention. Moreover, anticipated perceptual action-effects influence the way concurrent visual events are prioritized. Finally, expanding the view of actions as building blocks of higher cognition expands the scope and implications of the action-based attention research. The way in which conceptual understanding influences perception, seems to reflect the same characteristics of their constituent action elements.

Joint attention

An action-centered representation gives us command over a complex, although often static environment. However, we frequently interact with other people, who are also capable of action. Thus, interacting with others requires that attention represents a nebulous exchange. Attention must select events caused by self and others. To solve this problem, we rely largely on joint representations: mechanisms that coordinate the representation of action across people. The first step of establishing this coordination is the use of joint attention: Directing attention to where a partner is attending (Sebanz, Bekkering, & Knoblich, 2006). In its most basic form, joint attention is demonstrated by using eye gaze as a spatial cue for attention. Targets are detected faster when preceded by a picture of a face looking in that direction (Friesen & Kingstone, 1998; Frischen, Bayliss, & Tipper, 2007). Another reliable cue for joint attention is hand gestures. Hands depicted in a grasping posture cue attention to targets that fit the grasp aperture, but inanimate apertures (U-shaped objects) do not

(Lindemann, Nuku, Rueschemeyer, & Bekkering, 2011). These studies show how the eyes and hands can direct another person's attention, thereby facilitating a shared representation.

There are several examples in the literature that show the coordination of perception and action can depend on whether a task is performed jointly or alone (Knoblich, Butterhill, & Sebanz, 2011). For example, the Simon effect can be distributed across two people when performed together (Sebanz, Knoblich, & Prinz, 2003). In this task, participants made left or right responses to the colour of a stimulus that also pointed left or right. Responses were slow when the response and stimulus are incompatible and fast when they are compatible (Simon, 1990). In some blocks, subjects performed half of the task, responding to only one colour while ignoring the other, effectively making it a go-no go task. Critically, they performed this task either alone or with another person who responded to the other colour (a complementary go-no go task). The compatibility effect (faster compatible / slower incompatible responses) emerged only when performing the go-no go tasks together, suggesting that the actors represented each other's responses (Sebanz et al., 2003).

Joint attention can also be achieved by attending to a partner's actions. In a joint IOR task, participants were slower to process stimuli at locations recently reached to by their partners (Welsh, Elliott, Anson, Dhillon, Weeks, Lyons, & Chua, 2005; Welsh, Lyons, Weeks, Anson, Chua, Mendoze, & Elliott, 2007). That observing another person's actions can induce IOR is strong evidence that attentional mechanism can operate on a task representation that is shared between individuals.

A similar demonstration of shared representation in joint actions occurs in demonstrations of Fitts' law. When reaching to targets, movement time (MT) scales to the difficulty of the action (Fitts, 1954). When bimanually tapping between two targets of different difficulties, MTs remain scaled to the harder target, as though compensating to maintain a rhythm (Mottet, Guiard, Ferrand, & Bootsma, 2001). Critically, when two people take aim at targets of different difficulties in an alternating, joint tapping task, their MTs scaled to the harder target, even though each participant's task did not depend on their partner's target (Fine & Amazeen, 2011). This result shows that participants represented their partner's task and achieved an interpersonal rhythm that compensated for the harder of the two tasks.

Finally, like the Simon effect and Fitts' law, action-based effects of reaching trajectory can be distributed across actors in a joint task. Griffiths and Tipper (2009) modified the selective reaching task (Tipper et al., 1992) to include two actors seated across from each other at a narrow table. Participants reached for a target in the presence of a distractor, taking turns with their partner. The researchers concluded that observing another person reach over a distractor evoked a simulation of the same reaching trajectory in later actions. The critical result in support of this conclusion was an upward deflection in the trajectory of the reach when the distractor was absent, after having watched a partner reach for the target when the distractor was present (Griffiths & Tipper, 2009). These effects of joint attention are all explained by assuming a shared task representation: Partners succeed in cooperation because their representations include one another's actions, abilities, and intentions.

Integration

The interaction of attention and action in the prioritization of visual information and the planning of actions is so ubiquitous, so efficient, and typically so successful that it guides our behaviours despite being in the very deep background of awareness. Indeed, the adaptive reciprocal relationship likely only comes to awareness when failures occur, and even then it is only a rough awareness that *something* went wrong rather than exactly *how* it went wrong (e.g., "I didn't see the sign post, even though it was right in front of me, and I drove my car right into it"). Such failures are often ascribed to failures of attention (as in the previous example; selecting the wrong bits of the visual field to send for further processing and inexplicitly discarding information that is both perceptually salient and mission critical), or errors of action planning (reaching for the salt but hitting a glass along the way and spilling the water in it). But as can be seen by the aforementioned studies, attention and action should be viewed as a continuous cycle of selection and action rather than entirely separate processes whereby one selects and the other acts. Put more eloquently by Dewey (1896), "… both sensation and perception lie inside, not outside the act" (p. 359). Such a view would take us away from looking at human performance as isolated stimulus-response episodes and bring into consideration such concepts as overlearned chains of sensorimotor and ideomotor associations. What James (1890) referred to as "habits" or stabilized tendencies that govern our relationship to our environments, can now become a subject of consideration within a framework that assumes a tight coupling between our actions and selective information processing.

While failures in the cycle of attention and action can produce serious, and even spectacular, consequences, these are the exceptions rather than the rule. As noted earlier, the reciprocal relationship of attention supporting action and action supporting attention is both very successful and ubiquitous in our everyday lives. Let's take the example of the relatively mundane task of shopping in a typical grocery store. Often, a person enters such a store with a list, written or mental, of a list of items to purchase. Let's suppose that the list includes a favourite type of boxed pasta and a specific type of small mushrooms. An older, modular, and sequential view of cognition might suggest that after allocating attention across the visual scene, the task salient box of pasta would be selectively attended to, and the relevant feature information for grasping the box (coordinates in space, size, orientation) would then be passed onto the motor system for the planning and production of the necessary limb movement. In other words, selecting the visual information of the desired pasta box would be independent of the action planning for obtaining the box, and vice versa.

A more integrated and continuous view of cognition, where action and attention are viewed as partners in determining behaviour, would suggest a very different set of processes are involved in the shopping trip. First, let us examine how attention will affect our actions. When searching for the right sized mushrooms in a bin of mushrooms, wrong sized mushrooms along the path of our hands will be more salient for action-based attention, and thus will produce more interference than wrong sized mushrooms beyond the path of our movement (as in Tipper et al.'s, 1992, selective reaching task). If a crowd has gathered to pick over the best remaining mushrooms, and someone has to reach across the passed-over mushrooms at the front of the bin, we might also reach with that avoidant trajectory, even if there are no bad mushrooms in our way (as in the joint attention task of Griffiths & Tipper, 2009). When looking for a specific pasta box, knowing the size of the box would alter our grip aperture, which in turn will aid attention is selecting the proper sized box from the array of boxes (Symes et al., 2008). If the type of pasta next to our goal pasta box is out of stock, the fact that there is a salient perceptual luminance contrast but no available alternative target (and therefore similar to an offset stimulus) means that lack of product will not interfere with the detection of the goal pasta box (Castiello, 1996). If, however, we are merely scanning the pasta boxes with no specific action goal, the blank space would likely attract attention (Welsh & Pratt, 2008).

Of course, grocery shopping is just one example of how the cycle of attention and action pervades our day to day lives. The example is perhaps as mundane as it gets; selecting the wrong sized mushroom or non-favorite pasta won't have a significant or long-term effect on our lives. But pilots selecting and acting on the proper controls in a commercial airliner, or drivers navigating through busy city intersections, surgeons operating on patients, are examples where the same interplay of attention and action is at work but the stakes are much higher. An awareness of how actions shape selection of information can lead to more practical strategies of how attention could be allocated and maintained on crucial information. In other words, when emphasis in training is on acquiring the right kind of attentional tendencies, it may prove useful to reformulate attentional tendencies as action tendencies. An action-oriented view of human performance stands in stark contrast to the passive information processing view in its potential in offering better strategies for performance success.

Future Directions

The study of action and attention has produced great insights into the cognition of human movement. Much of the great work by these scholars is discussed above. However, as in all subjects of inquiry, there remain many fascinating, unanswered questions for the field to address. In this section, we describe what we have identified as some pressing issues of practical and theoretical interest.

An action does not constitute a stable cognitive state, but rather is best conceived as a series of continually unfolding processes, which include planning, initiation, and control. Given this, one important question is how do these unfolding action processes parallel the way attentional processes treat sensory input? The Theory of Event Coding (Hommel et al., 2001), by proposing a distinct feature-binding stage that is enveloped by a larger feature-activation stage makes predictions with regard to the interference and facilitation of concurrent perceptual events. The theoretical work of Thomaschke, Hopkins, and Miall (2012a; 2012b) represents another attempt to distinguish between separate qualitatively-distinct stages of interaction between action and vision. The authors highlight how the planning stage is dominated by selection of categorical information (e.g., "left" vs. "right" key-press) while the control stage is dominated by continuous information (e.g., distance, size, etc.). The authors further propose an account of facilitation and interference that is grounded in the planning-control distinction (see also, Hommel, 2009; Zwickel & Prinz, 2012). Further research is necessary for reconciling the current theories.

A large portion of the changes to our sensory input is caused by our own actions (e.g., movements of the eye and body). Considering the distinction between self-caused and externally caused events would increase the ecological validity of attention research, especially given that the majority of attention research treats observers as passive recipients of information. Considering observers' role in bringing about perceptual information, and the observers' ability to learn and anticipate these changes can lead to novel and innovative lines of research on human visual attention. Current theories do not exactly predict the attentional consequences of identifying an event as self-caused (e.g., Waszak, Cardoso-Leite, & Hughes, 2012), and the available evidence seems to point toward diverging conclusions that self-caused events are sometimes prioritized (Desantis, Roussel, & Waszak, 2014) and sometimes de-prioritized (Cardoso-Leite, Mamassian, Schutz-Bosbach, & Waszak, 2010). Examining how attention operates within a context in which agents distinguish between self-caused and externally caused events represents a new and exciting line of research.

There is an extensive motor control literature on how actions are planned and produced, but not much of this detail has been examined in terms of possible effects on attention. For example, structured perceptual arrays invoke an exception to Fitts's Law of speed-accuracy trade-offs (e.g., Adam, Mol, Pratt, & Fischer, 2006; Pratt, Adam, & Fischer, 2007). Does this effect in action planning also influence how attention is allocated to grouped sets of stimuli?

The role of aging on the cycle of action and attention has not been extensively studied to this point in time. It is well-known that various components of the action and attention systems change with advancing age, but few studies have studied the possible interactions. As noted earlier, Bloesch et al. (2013), using a variation of the Tipper et al. (1992) distractor reaching task, found that older adults used egocentric frame of reference rather than the action-based frame of reference used by younger adults. Given this finding, it is likely that older adults will guide their behaviours through different variations of action and attention processes. This insight has practical implications for the way we design and plan environments for an aging population. It also has theoretical implications for the way attention and action systems develop over the lifespan.

Finally, a criticism that action-minded scientists occasionally level at the conventional paradigms of attention is that most attention studies bear no semblance to real world interaction, primarily because all of the traditional research occurs on computerized displays in tiny darkened rooms. This criticism is legitimate because the real world affords many actions (beyond button-presses), which can change how we process information. To some extent, this problem is mitigated by conducting studies in situations that demand real, dynamic, three-dimensional limb movements (e.g. Tipper et al., 1992; Bekkering & Neggers, 2002). Ironically, this criticism is perhaps becoming less externally valid as we spend more and more time acting on computers and other digital devices. Over half of Canadian, American, and European adults own a smartphone (Rooney, 2013), placing a computer display in their pockets at all times. Therefore, a return to digital displays is called for to round out the study on action and attention. This time, however, we should not think of the computer as a passive display of information (i.e., monitor and keyboard), but rather as a flexible action space (i.e, smart phone and tablet). This perspective leads to fruitful questions for future consideration. For example, does attention operate in the space surrounding a cursor with action-related priorities? If so, how should we design the optimal cursor? Human factors engineering is rich with literature aimed at designing displays (e.g. Johnson, Proctor, & Vu, 2004), but as of yet the lessons learned from studies on action and attention remain largely unapplied to human-computer interaction. Do the action-related priorities that attention exhibits in reaching and grasping translate to digital movements? Some evidence suggests this is the case, as the perceptual system's selectivity for grasping-relevant object features (e.g. Ganel & Goodale, 2003) extends to actions made with cursors (Janczyk, Pfister, & Kunde, 2013). However, further research is needed to determine how similar real and digital actions really are.

In summary, the study of action and attention has clearly demonstrated the inextricable bond shared by these faculties. Traditionally, psychologists thought of action and attention as separate systems – as though attention existed in a disembodied state that never moved through the world to gain new information or new perspectives. In light of the research and theory discussed in this chapter, we hope the reader will agree that action and attention are two sides of the same coin.

Key Points

- Attention and eye movements are reciprocally linked; preparing saccades moves attention and moving attention primes saccades. This is evidence for the influential premotor theory of attention, which states that attentional orienting is contingent on the covert preparation of eye movements.
- The link between action and attention goes beyond eye movements. Performing, or intending to perform, a manual action affects selection of available information. Perceptual dimensions that are relevant for successful completion of the action tend to be favoured, and perceptual features that match the features of the current action are selected more efficiently. Perceptual anticipation that accompanies an action also influences the way concurrent perceptual events are prioritized.
- Attentional processes do not only take one's own actions into account but also the actions and intentions of our co-actors. In other words, selection of information takes place from a representation of environment that can include other people.

Future Directions

- Psychologists must consider the extent to which attention and action are truly separate, if at all. Attention selects the information necessary for action, and action moves the observer (and manipulates its environment) to new information. Does it make sense to discuss action and attention as though they are separate faculties?
- Compared to passive viewing, how do different aspects of an action, such as planning, initiation, and on-line control, shape selection of information from the environment? In particular, if an action accompanies perceptual anticipation, how do such anticipation differ from other forms of perceptual expectations that do not involve an action?

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