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Attentional resource allocation during a cued saccade task

W.E. Huddleston *, M.S. Aleksandrowicz, A. Yufa, C.R. Knurr, J.R. Lytle, M.M. Puissant

Department of Kinesiology, University of Wisconsin-Milwaukee, Milwaukee, WI, USA

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ABSTRACT

Attentional selection of sensory information and motor output is critical for successful interaction with one's surroundings. However, organization of attentional processes involved in selection of salient visual information, decision making, and movement planning has not yet been fully elucidated. We hypothesized that attentional processes involved in these tasks can function independently and draw from separate resources. If true, challenging the capacity limit of one attentional process would not affect performance of others. Healthy participants performed a cued saccade task in which target cues were embedded in a central stream of letters in a Rapid Serial Visual Presentation (RSVP). Participants performed saccades as quickly and as accurately as possible to a peripheral target location based on cue presentation within the central letter stream. To challenge visual attention, we parametrically varied the duration at which each letter of the RSVP was presented (50–200 ms). In a separate experiment we challenged motor attention by increasing the number of possible saccade trajectories (1–6 peripheral targets). As expected, increasing attentional load in one domain of the task negatively affected performance in that domain, while performance in other domains was unaffected. We interpret our results as support for the independent allocation of attentional resources, at least in the early stages of processing, required across components of a cued saccade task. Deciphering the contributions of attention during visuomotor tasks is a critical step to understanding how humans process information necessary to successfully interact with the environment.

1. Introduction

Purposeful interaction within one's environment often requires task-relevant sensory information to guide actions of the motor system. For example, the visually derived spatial location of a water glass is needed for a person to successfully reach for the glass. The selection of salient sensory information (Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1990; Handy & Mangun, 2000; Huddleston & DeYoe, 2008; Moran & Desimone, 1985; Posner, Cohen, & Rafal, 1982) and correct motor response (Castiello, 1999; Pashler, 1991; Rushworth, Paus, & Sipila, 2001; Symes, Ottoboni, Tucker, Ellis, & Tessari, 2010) occurs by attentional processes. How attentional resources are distributed to sensory, cognitive, and motor components of a task is a topic of longstanding debate. Is attention for sensory selection, decision making, and motor selection inextricably linked or does attention operate as separate brain processes for different components of a task? The answer to this dilemma significantly affects how one considers brain organization and has practical implications on issues such as brain–computer interfaces and rehabilitation of people with disorders such as hemispatial neglect. Controversy currently exists between the uses of integrated sensorimotor versus domain-specific approaches for both fields (Cicerone et al., 2011; Dromerick et al., 2009; Gordon et al., 2011).

Arguments have been made for a single attentional mechanism (Brisson, Leblanc, & Jolicoeur, 2009; Kuhn, Keizer, Colzato, Rombouts, & Hommel, 2011) in which visual attention and eye movements are not dissociable. The most common of these theories include the Pre-Motor Theory of Attention (Rizzolatti, Riggio, Dascola, & Umilta, 1987) or the Visual Attention Model (Schneider, 1995). Others argue for a minimum of a common coding scheme (Zwickel & Prinz, 2012) or the same synaptic mechanisms (Brown, Friston, & Bestmann, 2011). Conversely, other researchers have provided evidence for the presence of separate, yet closely linked, visual attention and motor attention processes (Fagioli, Hommel, & Schubotz, 2007; Hu, Bu, Song, Zhen, & Liu, 2009; Ikkai, Jerde, & Curtis, 2011; Montagnini & Castet, 2007; Pashler, 1991; Symes et al., 2010). Gottlieb and Balan (2010) argue that visuomotor decision-making cannot be done in a single stage, but rather requires separate stages to allow for behavioral flexibility. The Affordance Competition Hypothesis (Cisek, 2007) provides a computational model allowing for parallel processing throughout a visuomotor task. Also, data from patients with cortical lesions support a model with separate attentional mechanisms as they show a functional task-dependent dissociation between visual and motor attention (Mattingley, Husain, Rorden, Kennard, & Driver, 1998; McIntosh, McClements, Dijkerman, Birchall, & Milner, 2004; Persad, Jones, Ashton-Miller, Alexander, & Giordani, 2008; Rushworth, Nixon, Renowden, Wade, & Passingham, 1997).

* Corresponding author at: University of Wisconsin-Milwaukee, College of Health Sciences, Department of Kinesiology, PT-PAV350, P.O. Box 413, Milwaukee, WI 53201-0413, USA. Tel.: +1 414 229 3368 (office); fax: +1 414 229 3366.
E-mail address: huddlest@uwm.edu (W.E. Huddleston).

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A number of studies investigating the role of attention in visually-guided motor tasks have used multiple experimental approaches, including a dual-task paradigm (Bonfiglioli, Duncan, & Rorden, 2002; Brisson et al., 2009; Deubel & Schneider, 1996; Pashler, 1991). While powerful, the comparison of attentional resource allocation across two tasks prevents analysis regarding the specific interaction among visual, cognitive and motor systems during a single act. Dual task paradigms lead to increased cognitive costs when compared to performing only one task (Kristjansson, Wang, & Nakayama, 2002; Pashler, Carrier, & Hoffman, 1993; Stuyven, Van der Goten, Vandierendonck, Claeys, & Crevits, 2000). Also, many of the dual task paradigms probe visual attention by the subjects' ability to identify a pop-out visual probe. This approach specifically assesses subjects' exogenous attentional capture, while motor attention is focused elsewhere, and does not address the relation between voluntary visual attention and motor attention. Another approach has been to use a Posner-type paradigm with advanced valid and invalid cuing regarding the location of an upcoming visual probe prior to a response (Brown et al., 2011; Rizzolatti et al., 1987; Rushworth et al., 1997). In this case, motor responses typically involve button presses, which do not require any direct spatial information to perform that component of the task. Yet other researchers have directed motor attention to effector selection rather than trajectory selection (Kuhn et al., 2011; McIntosh et al., 2004; Rizzolatti et al., 1987). Although all of these studies are important in their own right, they leave open the issue of the extent to which attentional contributions to a visuomotor task operate independently of one another in a single spatially demanding task with one effector. In the present study, we used a cued saccade task in which we 1) varied visual attention load (Experiment 1) or motor attention load (Experiment 2) in a single task, 2) physically separated the spatial location of the visual component of the task from the saccade end targets, 3) focused motor attention on saccade trajectory selection rather than effector selection, and 4) required endogenous attention to perform all components of the task. A task in which both visual and motor components necessitates voluntary attention may be more ecologically valid as a person commonly moves towards a self-selected object with the desired limb rather than towards one that has visually salient physical properties.

In the current study, we hypothesized that attentional processes participating in visual perception, decision making, and motor performance components of a cued saccade task draw from independent attention resources. For this set of experiments, we define visual attention as the selection of salient cues from all distractors, consistent with previous studies (James, 1890; Johnston, McCann, & Remington, 1995; Maddox & Dodd, 2003). Motor attention has been previously described as involving the selection of both movement trajectory and effector (Rushworth, Ellison, & Walsh, 2001). Because effector selection (the eyes) was determined by the task and did not change over the course of the experiment, we define motor attention as the selection of the correct and accurate saccade trajectory (Goldberg & Segraves, 1987; Hommel & Schneider, 2002; Pashler, 1991; Rushworth et al., 1997; Symes et al., 2010). In our task, the correct stimulus–response pair also had to be selected from all six pairings, and we define this cognitive process as decision making. We capitalized upon known capacity limits of attention (Hommel & Schneider, 2002; Lavie & de Fockert, 2003; Navon & Gopher, 1979; Todd & Marois, 2004) to test our hypothesis. Attentional processes cannot be directly measured, thus we monitored changes in visual perception, trajectory selection, and motor performance as indicators of challenges to visual attention and motor attention, respectively. If attentional resources are shared across all modalities, varying either visual or motor attentional load would affect all aspects of the task leading to longer reaction times, higher perceptual error rates, trajectory selection errors, and greater movement inaccuracy. If attentional processes do not share resources across task components, challenging one attentional component of the task would not affect performance in other domains, where visual performance is measured by successful perception of cue letters, decision making by correct trajectory selection, and motor performance by saccade landing accuracy, and saccade landing variability. In Experiment 1, we varied the visual attentional load during a cued saccade task, which would directly affect visual perception (Handy & Mangun, 2000; Lavie & Tsal, 1994; Theeuwes, Kramer, & Belopolsky, 2004), and assessed the effect on perceptual and motor performance. In Experiment 2, we increased the number of possible saccade trajectories, challenging motor attention, and evaluated performance across task domains. Preliminary results from these two experiments have been presented elsewhere (Huddleston, Aleksandrowicz, & Yufa, 2008; Huddleston, Lytle, Puissant, & Yufa, 2010).

2. Materials and methods

2.1. Subjects

Twenty healthy participants, with normal or corrected-to-normal vision, took part in each of the two experiments (Experiment 1: 8 females, 12 males; 18–41 years, mean 23.2 years; Experiment 2: 11 females, 9 males; 18–43 years, mean 24.5 years). Some participants participated in both experiments, although experimental data were not collected on the same day for anyone. All participants provided written informed consent as approved by the University of Wisconsin-Milwaukee Institutional Review Board. Exclusion criteria included an inability to sit comfortably for extended periods or self-report of orthopedic or neurological conditions affecting performance on the task.

2.2. Stimulus and task

The purpose of the present paper was to determine the extent to which performance on different components of a cued saccade task could be altered by changing the visual (Experiment 1) or motor (Experiment 2) attentional load.

2.2.1. Experiment 1

Participants sat 70 cm in front of a monitor with their heads stabilized via a chin rest. Subjects performed saccades as quickly and as accurately as possible to peripheral targets when cued to do so based on a centrally located cue. The stimulus display for Experiment 1 (Fig. 1) consisted of four peripheral targets (13° eccentricity) labeled “A”, “B”, “C”, and “D” presented on the monitor and were fixed throughout the experiment. Centrally, a Rapid Serial Visual Presentation (RSVP) of random letters occurred. Target letters were randomly presented within a string of distractor letters consisting of the other 22 letters of the alphabet. Each cue letter was presented four times within the run, never occurring less than two seconds apart in all conditions to allow subjects time to complete the saccade prior to the next cue letter being presented. An individual trial was considered to be the time between cue letter presentations. We parametrically varied the difficulty of the visual component of the stimulus by altering the duration of letter presentation in the RSVP stream from 200 ms in the easiest condition to 50 ms in the most difficult condition (200, 150, 125, 100, 75 and 50 ms). RSVP letter duration was maintained within runs. We chose to challenge visual attention by altering the length of time in which a cue letter was shown while maintaining the same number of cues to be identified and the same duration between trials. In this task, attentional selection is required over time, rather than across space, to improve target letter perception with diminished letter-viewing times. Other methods of challenging visual attention in similar tasks often include altering the number of cues required to be identified (Culham, Cavanagh, & Kanwisher, 2001; Tomasi, Chang, Caparelli, & Ernst, 2007) or by establishing complex rules regarding cue presentation requiring a motor response (Gould, Nobre, Wyart, & Rushworth, 2012; Kamke et al., 2012). Both of these alternate approaches to challenging visual attention would not serve our purposes, as working