Vision Research 113 (2015) 71–77

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Allocation of cognitive resources in comparative visual search – Individual and task dependent effects

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ARTICLE INFO

Article history:
Received 28 July 2014
Received in revised form 31 March 2015
Available online 18 June 2015

Keywords:
Decision making
Comparative visual search
Working memory
Gaze movement
Individual trade-off

ABSTRACT

Behaviors recruit multiple, mutually substitutable types of cognitive resources (e.g., data acquisition and memorization in comparative visual search), and the allocation of resources is performed in a cost-optimizing way. If costs associated with each type of resource are manipulated, e.g., by varying the complexity of the items studied or the visual separation of the arrays to be compared, according adjustments of resource allocation ("trade-offs") have been demonstrated. Using between-subject designs, previous studies showed overall trade-off behavior but neglected inter-individual variability of trade-off behavior. Here, we present a simplified paradigm for comparative visual search in which gaze-measurements are replaced by switching of a visual mask covering one stimulus array at a time. This paradigm allows for a full within-subject design. While overall trade-off curves could be reproduced, we found that each subject used a specific trade-off strategy which differ substantially between subjects. Still, task-dependent adjustment of resource allocation can be demonstrated but accounts only for a minor part of the overall trade-off range. In addition, we show that the individual trade-offs were adjusted in an unconscious and rather intuitive way, enabling a robust manifestation of the selected strategy space.

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1. Introduction

A major objective of executive functions (Alvarez & Emory, 2006; Ardila, 2008) is the generation of adequate behavior in order to solve a given task by trading-off the arising costs and benefits. Costs or pay-offs are consequences in such decision making processes, where the relative values of different behavioral strategies are critical and have to be known or learned.

Cost-benefit analyzes are relevant in cognition as well as in economics to promote efficiency. In the field of economics, as example, researchers address the minimum cost flow problem (Ahuja, Magnanti, & Orlin, 1993). Here, as part of optimization in a deterministic transportation network, cost flows related to transportation demands (time, energy, etc. of industrial goods) should be minimized leading to economically advantageous solutions. Similarly, cognitive heuristics (Marsh, Todd, & Gigerenzer, 2004) discusses cost-benefit balancing on cognitive grounds – as a way of increasing efficiency by applying intuitive, rational, and adaptive decisions based on cognitive and perceptual operations (e.g., ACT-R; Anderson, 1993). In an ongoing debate, the characteristics of optimality regarding eye movement behavior in visual search (i.e., spatiotemporal characteristics of saccades), is discussed with either statistical models (e.g., bayesian ideal observer analysis; Najemnik & Geisler, 2005) or by simple heuristic rules (e.g., Morvan & Maloney, 2012; Tatler & Vincent, 2009). In this way, saccadic decisions might be based on a computation that requires knowledge of visual sensitivity maps or on heuristic preferences for saccades of certain lengths (e.g., the tendency to saccade to the center of mass of clusters of objects in the periphery). Additionally, Simon (1955) argued that optimality is not necessarily what biological systems are trying to achieve but instead seeking solutions that are 'good enough' for their purposes and do satisficing (i.e., it is often 'rational' to seek to satisfice in that the process of looking for better solutions/results expends resources).

In cognitive science, comparative visual search (CVS) is a well-established task to investigate decision processes (cost-benefit balancing) under controlled and changing task demands. In CVS subjects have to compare two or more visually separated arrays of items in order to find differences between them (Ballard, Hayhoe, & Pelz, 1995; Bauhoff, Huff, & Schwan, 2012; Hardiess, Gillner, & Mallot, 2008; Pomplun et al., 2001). When inspecting one of the arrays, information about the other one has to be kept in mind in order to carry out the comparison. Required memory involvement can be reduced by frequent

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http://dx.doi.org/10.1016/j.visres.2015.05.017
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re-acquisition of information from the reference array. For an efficient overall strategy, the investment in memorization as well as acquisition (exploration) behavior must be traded-off. Memorization or processing strategies are implemented by visual working memory (WM). Here, the purpose of WM is to enable the short-term retention and manipulation of information in the service of immediate action. Acquisition or sensorial strategies are reflected by gaze movements and involve saccadic (orienting the sensors toward informative areas) as well as fixational (extracting item information) movements.

In general, WM can be defined as a system for maintaining and processing a certain amount of information temporarily for the task at hand (Baddeley & Hitch, 1974; Phillips, 1974) and is subject to temporal (Magnussen et al., 1991; Ploner et al., 1998; Zhang & Luck, 2009) as well as storage capacity limitations (Alvarez & Cavanagh, 2004; Luck & Vogel, 1997). WM representations decay within several seconds when no active rehearsal processes (refreshing of memory) take place (McAfoose & Baune, 2009). Regarding storage capacity, visual WM processes information of approximately three to five items at a time, but the way of coding such items is debated controversially as object-based (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001), as a collection of separated visual features (Wheeler & Treisman, 2002), or as a probabilistic feature-store model (Fougnie & Alvarez, 2011). Additionally, WM capacity limitations are discussed in two lines of theory. The *fixed-resource theory* (Zhang & Luck, 2008) conceptualizes WM as limited-capacity channel with a fixed number of slots over which observers can flexibly allocate information with fixed precision. In this view, a complex item (object) will allocate more slots for retention than a simple one. The other class of theories (*flexible-resource*) claims that WM capacity is limited by the availability of processing resources (Bays & Husain, 2008). Here, the maintenance of an item requires some amount of cognitive effort and applying this effort depletes the resource pool. As a consequence, an observer can either maintain a low amount of precisely-represented or a higher amount of less-precisely encoded items before resources run out.

Several studies could show that the investments in acquisition or memorization were balanced so as to optimize the associated time costs (Ballard, Hayhoe, & Pelz, 1995; Droll & Hayhoe, 2007; Gray et al., 2006; Hardiess, Basten, & Mallot, 2011; Hardiess, Gillner, & Mallot, 2008), i.e., subjects adjusted the trade-off between acquisition and memorization to minimize overall time when the individual time requirements for the one or other strategy were changed. When overall costs for gaze movements remain low, assumingly the normal state in everyday tasks, subjects will shift the trade-off almost completely to the side of acquisition, i.e., picking up information continuously from the environment just when needed. Such a ‘just-in-time’ strategy (Ballard, Hayhoe, & Pelz, 1995; Hardiess, Basten, & Mallot, 2011) minimizes the investment in memorization and enables WM capacities for other tasks which have to be carried out at the same time. When acquisition becomes more costly (i.e., by increasing the distance between stimulus arrays and so the time needed to capture the information), it was found that subjects increasingly relied on memory processes rather than on acquisition movements (Ballard, Hayhoe, & Pelz, 1995; Hardiess, Basten, & Mallot, 2011; Hardiess, Gillner, & Mallot, 2008; Inamdar & Pomplun, 2003). However, the degree of such a shift to memory strategies is restricted by the inherent processing limits of the WM structures involved (see above).

In the present investigation, a simplified desktop version of the CVS paradigm was developed in order to easily manipulate the burden costs and to quantify the strategies for acquisition (gaze shifts between arrays of items) and memorization (fixations needed for information processing within arrays) without measuring gaze behavior directly.

Acquisition costs can be controlled by varying inter-array separation (Ballard, Hayhoe, & Pelz, 1995; Hardiess, Basten, & Mallot, 2011; Hardiess, Gillner, & Mallot, 2008; Inamdar & Pomplun, 2003). Clearly, spatial separation will always be associated with time needed for re-acquisition (Hardiess, Gillner, & Mallot, 2008). We therefore developed a task in which re-acquisition time is explicitly controlled. During the CVS task one of the two arrays was covered by an opaque mask that could be switched to the other array by hitting a mouse button.

Memorization costs are determined by the required amount of processing, both in perception and memorization. On the perception side, higher costs arise when items entail more features to be extracted, bound, and recognized. Memorization in CVS becomes more costly with respect to information load and the capacity limit of the WM system (Alvarez & Cavanagh, 2004), when items increasingly demand encoding, maintenance, recall, and comparison operations. In our study, we therefore varied the complexity of the comparison items effecting perception as well as memorization in WM (Luria et al., 2010).

Previous studies on acquisition-memorization trade-offs mostly employed between-subject designs. This leaves open the question whether observed strategy shifts result from subject-specific preferences for one or the other strategy, or from adjustments to the cost constraints applied by all subjects in similar ways. In this study, we use a simplified CVS procedure to assess in one within-subject design both, the strategy distribution in the group and the trade-off behavior in each subject.

2. Material and methods

2.1. Participants, apparatus, and stimuli

Twenty nine volunteers (15 males) aged between 22 and 30 years participated in the study. All subjects were naïve to the purpose of the experiment and had normal or corrected to normal vision. All experiments adhered to the Code of Ethics of the World Medical Association (Declaration of Helsinki) and a written informed consent was obtained from each subject prior to participation.

A personal computer (3.1 GHz) running MATLAB (MathWorks Ltd.) was used for stimulus presentation, experiment control, and recording subjects’ responses. The software controlling the experiment incorporated the Psychophysics Toolbox extensions (Brainard, 1997). Stimuli were displayed on a Samsung SyncMaster 931BF monitor (19″, 1280 × 1024 pixel, 60 Hz) driven by the computer’s built-in Intel®HD Graphics 2000 graphics board. The viewing distance between subject and monitor was 60 cm (chin rest used) and stimuli were viewed in a dimly lit room.

Each trial (stimulus) of the CVS task consists of two columns (separation: 24 degrees of visual angle) with 24 symbols (randomised order) each. Two types of symbols were used (see Fig. 1) to manipulate the processing costs: colored circles as low cost items (i.e., color condition; red, green, blue, and black; 0.29° visual angle) and silhouettes of animals as high cost items (i.e., object condition; black elk, dog, camel, and cow; all leftward-facing; 0.86° visual angle). For the comparison task, the symbol configurations in the two columns differed at one or two random positions (one- and two-differences, respectively). A maximum number of two differences was introduced to avoid premature trial completion. Because subjects did not know the number of differences, they should not terminate the search after detecting the first difference. During all trials an opaque gray mask was always presented, covering either the left or the right column completely (the right one in the beginning of a trial; Fig. 1). Between each pair of symbols a black line was always shown (over the

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