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Research report

New insights into feature and conjunction search: I. Evidence from pupil size, eye movements and ageing

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ABSTRACT

Differences in the processing mechanisms underlying visual feature and conjunction search are still under debate, one problem being a common emphasis on performance measures (speed and accuracy) which do not necessarily provide insights to the underlying processing principles. Here, eye movements and pupil dilation were used to investigate sampling strategy and processing load during performance of a conjunction and two feature-search tasks, with younger (18–27 years) and healthy older (61–83 years) age groups compared for evidence of differential age-related changes. The tasks involved equivalent processing time per item, were controlled in terms of target–distractor similarity, and did not allow perceptual grouping. Close matching of the key tasks was confirmed by patterns of fixation duration and an equal number of saccades required to find a target. Moreover, moment-to-moment pupillary dilation was indistinguishable across the tasks for both age groups, suggesting that all required the same total amount of effort or resources.

Despite matching, subtle differences in eye movement patterns occurred between tasks: the conjunction task required more saccades to reach a target-absent decision and involved shorter saccade amplitudes than the feature tasks. General age-related changes were manifested in an increased number of saccades and longer fixation durations in older than younger participants. In addition, older people showed disproportionately longer and more variable fixation durations for the conjunction task specifically. These results suggest a fundamental difference between conjunction and feature search: accurate target identification in the conjunction context requires more conservative eye movement patterns, with these further adjusted in healthy ageing. The data also highlight the independence of eye movement and pupillometry measures and stress the importance of saccades and strategy for understanding the processing mechanisms driving different types of visual search.

1. Introduction

The visual search paradigm has long been used as a means of investigating selective attentional mechanisms in vision and also the manner in which these are affected by ageing. Typically, the participant looks for a specific target element within a display of distractor elements and responds either "yes" if a target is found, or "no" if they decide a target is absent. Such

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tasks are traditionally divided into two categories: feature search and conjunction search (see Treisman, 1988). Feature search, where the target is defined by a single feature (e.g., a red target among green distractors), is often known as ''pop-out'' search because of the ease with which the target can be identified regardless of the number of distractors. In conjunction search, however, the target is defined by a unique combination of features (e.g., a red vertical target among red horizontal and green vertical distractors), and search times are slower and increase with the number of distractors. Although these two search scenarios undoubtedly differ in the processing required for successful performance, the processing differences do not necessarily arise from the target definition differences (i.e., a single feature *vs* a conjunction of features). A number of factors, which may be largely independent of the feature/conjunction distinction, are now thought to contribute to the contrasting behavioural patterns described; e.g., the visual similarity between different distractors (Duncan and Humphreys, 1989). Nevertheless, a key fundamental question remains unanswered: does the recognition of a conjunction-defined target, requiring the combination of information on multiple feature dimensions, inevitably involve different neural processes from the recognition of a single-feature target? The answer to this is central to our understanding of how objects, with their unique combination of numerous features, are recognised. In the work reported here, we sought to address this question by controlling the factors which we know typically co-vary with the two search task types (i.e., search speed, attentional shifting and item similarities). We examined the resultant comparable feature and conjunction tasks using psychophysiological measures not previously applied to this issue (pupil dilation and eye movements), and compared the results across different age groups.

The initial idea that a single-feature-search task involves rapid processing while a conjunction task requires slow attentional mechanisms is no longer accepted: we now know that feature search may be slow (e.g., Treisman and Souther, 1985; Treisman and Gormican, 1988) while conjunction search may be fast (e.g., Nakayama and Silverman, 1986; Treisman and Sato, 1990; Enns and Rensink, 1991; Theeuwes and Kooi, 1994). Instead, feature and conjunction searches are seen to lie on an overarching continuum of ''search efficiency'', as indexed by the processing time per item (the ''search slope'' of the function relating response time to number of elements in the display). Efficient searches have flat slopes (maybe $<$10 msec per item), whereas inefficient searches have steeper slopes, maybe 30–40 msec per item or more (see Wolfe, 1998, for a review). While feature searches are often efficient and conjunction searches inefficient, this is not inevitably the case. Note that the concept of search efficiency is separate from visual search theories as it makes no claims about the underlying processing mechanisms. However, it would be expected that searches differing markedly in efficiency would differ in processing in some way, whether qualitatively or quantitatively. In the work reported here, therefore, we matched our feature and conjunction tasks as closely as possible in terms of search efficiency, as assessed by search slope, in order to see if the psychophysiological measures nevertheless indicated task-related differences in processing.

Originally, the feature/conjunction distinction was thought to be inevitably tied up with differences in attentional deployment. According to Treisman and Gelade (1980), single-feature search involved inspecting one ''feature map'' (colour, in our example) for the presence of a unique feature: an automatic, pre-attentive and parallel search process. In contrast, an attentive and serial mechanism was proposed for conjunction search: information from different feature maps (e.g., colour and orientation) must be combined, and it was suggested that this ''feature binding'' process required attention to be directed to each location in turn, hence the slower search speed, varying with the number of items (see also Treisman and Gormican, 1988). The ''feature binding'' aspect of this theory, exclusive to conjunction discriminations, is the focus of our investigation, but is no longer seen as intrinsically linked with attentional shifts as opposed to the parallel gathering of information (see Wolfe, 1998). However, a development of the parallel/serial processing distinction is that certain types of (typically efficient, single feature) search arrays allow for similar non-target items to be perceptually grouped and hence rejected together much more easily than other display types (e.g., in inefficient conjunction tasks). The perceptual grouping of items for attentional deployment remains central to current explanations of search-type differences (e.g., Duncan and Humphreys, 1989; Wolfe, 1994). Consequently, in order to compare the target-identification processes for single feature and conjunction searches without a potential grouping confound, we designed stimuli surrounded by rings, which required foveation and should therefore prevent grouping equally across task types (see Fig. 1a).

A further, related consideration generally confounded with the classic feature/conjunction behavioural distinction is the discriminability of targets and distractors. Duncan and Humphreys (1989) showed that search efficiency increases as targets and distractors become less similar and/or distractors and other distractors become more similar (see also Phillips et al., 2006). Feature search often involves low target–distractor similarity and high distractor–distractor similarity, while the reverse is generally true of conjunction search; thus it could be that feature-conjunction differences arise entirely because of item similarity effects rather than any fundamental difference in the processes required for target recognition in each. In this study, we matched distractor–distractor similarity across feature and conjunction tasks (F45 and Con in Fig. 1). Note that perfect matching of target–distractor similarities across such tasks is simply not possible: by definition, the target in a single-feature task differs from distractors on only one dimension, while a conjunction target differs from distractors on two dimensions. Consequently, in order to understand the impact of target–distractor similarity effects upon our measures, we included a second feature-search task (HF in Fig. 1), with lower target–distractor similarity than the other tasks. To keep overall efficiency as closely matched across the tasks as possible, this third task had lower distractor–distractor similarity (Duncan and Humphreys, 1989).

If these typically co-varying factors (search efficiency, item similarity and grouping processes) could be identical across feature and conjunction search tasks, then it is likely that any differences manifested during performance would be attributable to differential recognition processes involved in matching