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A compact field guide to the study of microsaccades: Challenges and functions

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ABSTRACT

Following a period of quiescence at the end of last century, the study of microsaccades has now regained strong impetus and broad attention within the vision research community. This wave of interest, partly fueled by the advent of user-friendly high-resolution eyetrackers, has attracted researchers and led to novel ideas. Old hypothesis have been revisited and new ones formulated. This article is designed to serve as a practical guide for researchers in the field. Because of the history of the field and the difficulty of measuring very small eye movements, the study of microsaccades presents peculiar challenges. Here, we summarize some of the main challenges and describe methods for assessing and improving the quality of the recordings. Furthermore, we examine how these experimental challenges have influenced analysis of the visual functions of microsaccades and critically review current evidence on three long-debated proposals: the maintenance of fixation, the prevention of visual fading, and the exploration of fine spatial detail.

1. Introduction

Vision is an active process. In humans, like in many other species, photoreceptors are not uniformly distributed across the retina, but their density progressively declines starting from a small region approximately at the center of the fovea. As a consequence, humans acquire visual information during brief periods of fixation separated by saccades, the rapid eye movements that enable inspection of the objects of interest with this high-acuity region.

The term "fixation", however, is only partially accurate. Close examination of motor activity in the intervals in between saccades reveals that the eye is never stationary. During these periods, small eye movements, collectively known as fixational eye movements, incessantly perturb the gaze position. These movements occur even when attempting to maintain steady gaze on a single point. They consist of the continual alternation between miniature saccades (microsaccades or fixational saccades) and periods of erratic and relatively slow eye drifts.

Studies on fixational eye movements have primarily focused on microsaccades, which are easier to detect and measure (but see Kuang et al., 2012 for an example of recent study on drift). Microsaccades have drawn considerable interest both because they seem to occur without the observer's awareness and because of their small amplitude. Given that the primary function of eye movements is to inspect the target with the high-acuity region of the retina, what could be the function of saccades so small that maintain this region on the same object?

After being the subject of continuous investigation for large part of last century, interest in microsaccades waned in the 1990s, to then surge back into a full wave of active research this century, when a new generation of non-invasive and easy-to-operate eyetrackers with resolution sufficient to examine small saccades became available. As part of this new wave of interest, old hypothesis have been revisited and new ones proposed. This broader access to the study of small eye movements has, however, not always being accompanied by the necessary appreciation of the facts already established by the previous literature and/or full consideration of the challenges inherent in the study of very small eye movements (see Collewijn & Kowler, 2008 for an excellent discussion of these issues). These are serious concerns, as failure to pay attention to present challenges and previous accomplishments comes at the risk of adding confusion, together with new knowledge, to the field.

The purpose of this article is not to provide yet another review on microsaccades, but to serve as a practical guide to the study of small eye movements and as an introductory source for new researchers in the field. In the following pages, we analyze critical challenges presented by microsaccades and describe some possible solutions. We also examine how experimental challenges have

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influenced the quest for the visual functions of eye movements and summarize our viewpoint on three long-debated hypotheses. Our conclusions are simple: (a) we agree with previous observations that great caution is necessary in extrapolating laboratory results to more natural conditions; and (b) argue that when the artificial condition of sustained fixation is not enforced and observers can move their eyes normally, most microsaccades serve an exploratory function similar to that of larger saccades.

2. Challenges associated with the study of microsaccades

Studying microsaccades requires more than a high-resolution eyetracker and a pool of committed subjects. Because of the long and complex history of the field, special attention needs to be dedicated to the design of the experimental conditions, the choice of controls, and the events that are selected as microsaccades. Furthermore, because of the extremely small size of the considered movements, technical knowledge of the recording methodology is required to a level that goes beyond the standard information provided by most eyetracker manufacturers. In this section, we discuss practical challenges associated with the study of microsaccades which may not be immediately obvious to new researchers in the field.

2.1. Defining microsaccades

What is a microsaccade? Difficulties in studying these small movements emerge even from their very definition, as little agreement exists on how they should be identified. Different studies have used the term in considerably different ways, and common definitions unfortunately depend on the specific task and experimental conditions under investigation, making it difficult to generalize scientific conclusions.

Microsaccades are often introduced as the "involuntary saccades that occur spontaneously during intended fixation" (*e.g.*, Rolfs, 2009 excellent review of the topic). This statement is typically accompanied by a subordinate clause specifying an amplitude threshold, which distinguishes microsaccades (saccades with amplitudes below threshold) from regular saccades (those with amplitudes above threshold). Although frequently used in the field, this definition implicitly comes with drawbacks: its dependence on the subject's intention (note the terms: "involuntary", "spontaneously", "intended") makes it little objective and prone to different interpretations. More importantly, this definition leads to the use of unnatural viewing conditions, which, as explained below, have contributed to ongoing confusion on the visual functions of microsaccades.

Consequences of a definition that relies on volition: A first difficulty in applying the microsaccade definition above originates from what is really meant by the term "involuntary". A common interpretation is that microsaccades are reflexive movements, and lack of awareness is often reported as evidence for such nature. Another interpretation is that microsaccades are unnecessary movements, because the projection of the stimulus is already on the preferred retinal locus of fixation. But both considerations are doubtful. Are microsaccades really "involuntary"?

As nicely pointed out by Collewijn and Kowler (2008), lack of awareness does not imply lack of voluntary control. Many movements which one would not categorize as involuntary are routinely made without explicit awareness, including saccades. Furthermore, microsaccades show clear signs of voluntary control. For example, they can be made in response to small displacements of the fixated target (Havermann et al., 2014; Timberlake et al., 1972; Wyman & Steinman, 1973) and to look in specified directions (Haddad & Steinman, 1973; Ko, Poletti, & Rucci, 2010). As we will discuss later in this article, microsaccades precisely relocate gaze toward nearby regions of interest in high acuity tasks (Section 3.3) and may be voluntarily executed also during sustained fixation, perhaps to compensate for fixation errors (Cornsweet, 1956). Indeed, in agreement with this hypothesis, it has long been known that microsaccades become less frequent by simply changing the instruction from "fixate" to "hold the eyes still" (Fiorentini & Ercoles, 1966; Steinman et al., 1967), and a similar rate reduction also occurs by removing the fixation marker (Cherici et al., 2012). Thus, microsaccades may not be as involuntary as one would intuitively assume. We will focus on this point in Section 3.1.

There is another, more fundamental problem which follows from a microsaccade definition that relies on volition. Since the experimenter has normally no way to determine whether the subject intends to maintain fixation, the definition given above can in practice only be used in experiments in which fixation is explicitly enforced. This requirement is typically achieved by asking subjects to maintain fixed gaze on a small cue (commonly a single point) for prolonged periods of time, a condition we will refer to as sustained fixation. This condition is a frequent requirement in vision research experiments, but rarely, if ever, happens in natural tasks, when the periods of inter-saccadic fixation only last a few hundreds of milliseconds. Sustained fixation has long been known to affect the pattern of fixational eye movements (Steinman et al., 1973) including microsaccades (Kowler & Steinman, 1980). Thus, the standard definition of microsaccades implicitly comes with specific and unnatural experimental requirements that alter oculomotor activity, the very focus of the investigation. In the following of this paper, we will often use the term "fixational saccades" to refer to the microsaccades performed under conditions in which observers are explicitly asked to keep their gaze at a fixed location.

Dealing with sustained fixation: Sustained fixation may also complicate the interpretation of experimental results in other ways. Sometimes this condition serves as a reference relative to which results obtained under other, perhaps more natural, conditions are evaluated. This use of an unnatural baseline may influence scientific conclusions. For example, a lower microsaccade rate observed in other tasks may not necessarily imply a suppression of microsaccades. Sustained fixation tends to yield frequent microsaccades in most observers (Cherici et al., 2012; Thaler et al., 2013), even if no stimulus other than the fixation marker is displayed (Fig. 4A).

In other cases, sustained fixation only serves as an auxiliary condition combined with another perceptual task, which is the primary focus of the experiment and the task to which investigators presumably dedicate their attention. Under these circumstances, the visual and oculomotor systems are simultaneously engaged in two activities: executing the task of interest *and* maintaining fixation. Both activities may trigger microsaccades, yet their occurrence may be erroneously attributed to the task of interest without consideration of the underlying requirement for maintaining fixation. This type of confusion has likely contributed to the long-standing controversy over the visual functions of microsaccades.

The possible influence of the explicit requirement of maintaining accurate fixation constitutes a general problem in vision research, which goes beyond the specific area of microsaccades. Various studies have now pointed out that fixational saccades may act as confounding factors in a number of situations. For example Yuval-Greenberg et al. (2008) showed that a certain class of gamma-band EEG responses, traditionally associated with higher cognitive functions, is time-locked with the onset of microsaccades, possibly reflecting a saccadic spike potential rather than higher-order processes. Indeed, several characteristics of this EEG signal mimic the dynamics of microsaccades. Herrington et al. (2009) reported that the occurrence of microsaccades can explain