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Fixational eye movements are not affected by abrupt onsets that capture attention

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Abstract

Recent work shows that abrupt onsets reflexively capture attention and trigger saccades that compete with voluntary saccades. To test whether oculomotor capture occurs when no saccade is being planned, we measured fixational eye movements in the absence or presence of an abrupt onset at peripheral locations. We found no effect of abrupt onset location on the average pattern of eye movements during fixation. We conclude that the capture of eye movements by an abrupt onset only happens when the oculomotor system has been preset to make a saccade. This implies that the oculomotor system is not obligatorily driven by events in the visual array. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Recent work by Irwin, Theeuwes, and colleagues (e.g. Irwin, Colcombe, Kramer, & Hahn, 2000; Theeuwes, Kramer, Hahn, & Irwin, 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999) shows that the oculomotor system makes automatic and stimulus-driven saccades to the abrupt onset of a new object in the visual array. But the task in each of their experiments was to make a saccade to some change-defined target. In Theeuwes et al. (1998, 1999) the target was change defined, albeit indirectly. There was no sudden change at the location of the target itself. Rather, the target was defined by change in that it was the only element that did *not* change color. When a new object appeared all at once at the same time as the change-defined target, a saccade was often made to this irrelevant distractor before a corrective saccade was made to the true target (compare McPeek, Skavenski, & Nakayama (2000)). They hypothesized that an abrupt onset automatically triggers preparation of a saccade to the onset location. According to their model, if this saccade is ready to execute before the task-relevant saccade, a saccade to the distractor will result. Because these incorrect saccades contradict the behavior demanded by the task, and presumably contradict top-down input into the circuitry that generates saccades, *their results can be taken as evidence that the oculomotor system is automatically driven by events in the visual array*. Indeed, incorrect saccades can even occur without the observer's conscious awareness that they have occurred (Theeuwes et al., 1998, 1999). However, incorrect saccades could also arise because the oculomotor system has been preset to make a saccade. In particular, the oculomotor system may be more biased to saccade to sudden local changes than to targets defined by a lack of change, as in the paradigm of Theeuwes et al. (1998, 1999). In contrast, if the oculomotor system is instead preset to maintain fixation rather than to make a saccade, then an automatic saccade to an abrupt onset may not occur. Thus, *if an abrupt onset does not influence eye movements during fixation, then we can conclude that the oculomotor system is not obligatorily driven by events in the visual array.*

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2. Theoretical background

It is not known whether eye movements during fixation are influenced by the abrupt onset of an object in the visual periphery. Theoretical evidence suggests that they might be. The attentional system is thought to have at least two subsystems, one involved in automatic and rapid shifts of "exogenous" attention to abrupt onsets (Irwin et al., 2000; Jonides & Yantis, 1988; Remington, Johnston, & Yantis, 1992; Theeuwes, 1994; Yantis & Hillstrom, 1994; Yantis & Jonides, 1984; Yantis & Jonides, 1990), and the other subsystem involved in volitional shifts of "endogenous" attention. The bottom-up subsystem is thought to involve circuitry in the superior colliculus (SC), and the top-down subsystem is thought to involve circuitry in the frontal lobe (Mesulam, 1981; Posner & Petersen, 1990). Similarly, saccade generation involves at least two parallel subsystems. A sub-cortical pathway involving the SC generates reflexive, orienting saccades, and a cortical pathway involving the frontal eye fields generates voluntary saccades via top-down input into the SC (e.g. Everling & Munoz, 2000; Hanes, Patterson, & Schall, 1998; Schall, 1995). Both the abrupt attentional shift and abrupt eye movement systems appear to recruit some of the same circuitry in the SC, one to move the direction of gaze and the other to move the focus of processing without necessarily moving the eyes (Corbetta et al., 1998; Kustov & Robinson, 1996; Rizzolatti, 1994; Robinson & Kertzman, 1995). If exogenously driven attentional shifts and saccades involve some of the same circuitry, then a stimulus such as an abrupt onset, which is known to automatically capture attention (e.g. Jonides & Yantis, 1988; Yantis & Jonides, 1984; Yantis & Jonides, 1990; Yantis & Hillstrom, 1994), may also automatically lead to saccades or microsaccades away from fixation. Moreover, the SC cells thought to trigger saccades may inhibit the SC cells that maintain eye fixation, and vice versa (e.g. Munoz & Wurtz, 1993). If an abrupt onset activates saccade cells in the SC, their activation might influence the behavior of fixation cells through their mutual inhibition. Thus, even if a saccade is not generated, evidence of the abrupt onset may be visible in the pattern of eye movements made during fixation.

3. Experimental design

To determine whether an abrupt onset in the visual array causes involuntary eye movements away from fixation, we carried out the following experiment. The observers' task was to attend to a large array of red and green squares while maintaining fixation. At the end of each trial, observers specified the color (red or green) of a new element that appeared during a global transient (for details, see Sections 4.4 and 4.5 below) in a flicker-

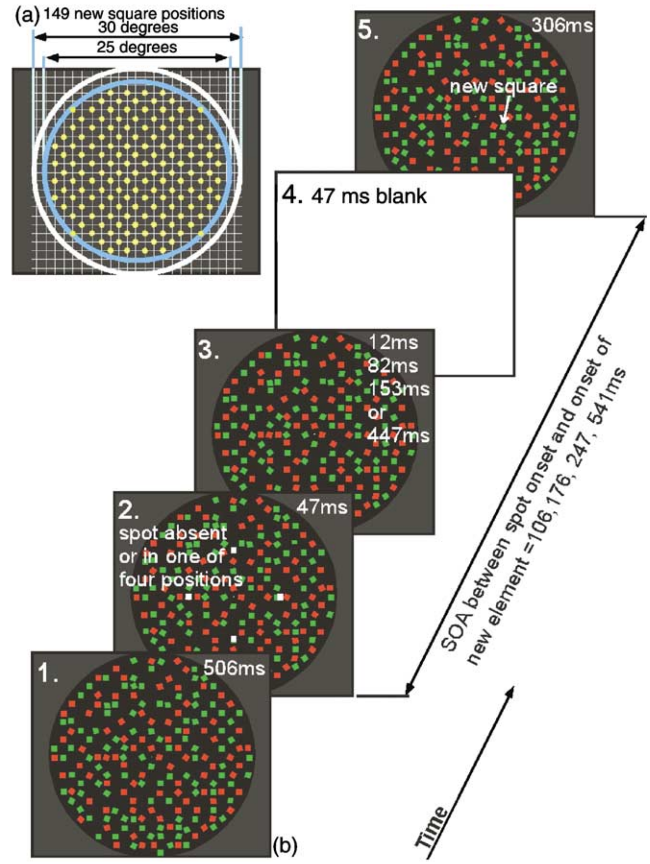

Fig. 1. Experimental design: the new square was shown in one of 149 positions of the array in the final frame (labeled 5 here) of the sequence in (b), indicated by yellow disks in (a), representing a subset of the overall grid that fit within an imaginary 25° circle centered at fixation. It always appeared in a random position that had been unoccupied on previous frames within a given trial. The final frame always contained one and only one new element. The observers' task was to maintain fixation and report whether the new element was red or green in a two alternative forced choice design.

induced change blindness paradigm (Rensink, O'Regan, & Clark, 1997). That is, observers pressed a button corresponding to either 'red' or 'green' after each trial. A single trial is schematized in Fig. 1.

Just prior to the occurrence of the global transient on each trial, there was either an abrupt onset on the positive or negative x- or y-axis (16/17th of trials), or there was no abrupt onset (1/17th of trials). The exact parameters of this abrupt onset are described in the Section 4.4 below. The purpose of this abrupt peripheral onset was twofold. First, its purpose was to draw the observers' attention to the location of that onset. This allowed us to test whether an abrupt onset has an influence on the distribution of correct answers in the red/green 2AFC task described above. These data were assumed to provide an indirect measure of the distribution of attention, and are described in detail elsewhere (Tse, Sheinberg, & Logothetis, 2002). Second, the occurrence of abrupt onsets allowed us to determine whether they influence fixational eye movements. For present purposes, the (red/green) data collected in the 2AFC task are irrelevant, because the question of interest here is whether abrupt onsets influence fixational eye movements.

4. Method

4.1. Participants

Four participants (24–38 years of age) carried out the experiment. Three paid observers were recruited from the Max Planck Institute subject pool, and one was the first author. All had normal or corrected to normal vision.

4.2. Apparatus

The visual stimulator was a dual processor Pentium II workstation running Windows NT (Intergraph Corp., Huntsville, Alabama) equipped with two VX113 graphics subsystems. The screen (Intergraph 21sd07 monitor) resolution was 1152×864 pixels and the frame rate 85 Hz. All image generation was in 24 bit truecolor, using hardware double buffering to provide smooth animation. The stimulation software was written in C and was based around Microsoft's OpenGL 1.1 implementation (with the client driver specific for Intergraph hardware). The 'Tool Command Language' (TCL) language was embedded within the stimulation software and was used for scripting. External control of the visual stimulator was achieved by using a high-speed ethernet connection between the real time control PC and the dedicated visual workstation using the realtime QNX operating system. Exact timing was verified by generating framebuffer swap synchronization pulses with a digital timer I/O card installed in the stimulator (ACL8454, Circuit Specialists Inc., Arizona) and monitoring them on an oscilloscope.

4.3. Eye monitoring

Observers were required to maintain fixation on each trial. Fixation was assured using an eyetracker (Sensomotoric Instruments, GmbH, Germany). A miniature video camera, attached to an adjustable headband and bar, was fitted about 2 cm below the subject's dominant eye, and eye movements were calibrated to a dot that moved to nine positions on the screen in random order. Observers rested their chin in a stable rest such that the distance from their eyes to the screen was 57 cm. The head was not otherwise constrained, although observers were instructed to maintain their head perfectly still. Small head movements could be discounted online by the eye tracker software using the output of four cameras mounted on the monitor. During the experiment, any time the subject's gaze was outside of a 1.5° radius fixation window, the trial would be automatically aborted and the new trial would be chosen at random from those remaining. If three trials were aborted in a row because gaze was outside the fixation window, the state system automatically reverted control to the eye tracker's calibration program. Once calibration was completed, the experiment resumed with a random trial. Drift in the eye tracking system could be treated by the state system as a failure to maintain fixation. Thus drift was tolerated up to 1.5°, whereupon recalibration was required. The experiment lasted between 35 and 50 min depending on the number of eye tracker recalibrations needed.

4.4. Stimuli

The fixation point was a 0.15° diameter yellow circle. The circular background shown in Fig. 1 was uniform black (<1 cd/m^2) and spanned the height of the monitor (30°). The background outside this circular region was dark gray. A 23×23 array of positions fit within a $30° \times 30°$ square that was partially occluded by this circular 'window'. All square stimuli were equiluminant red and green ($0.69° \times 0.69°$) as measured by a photometer (Minolta CRT color analyzer CA-100). Squares never overlapped. Their centers were at least 1.25° apart, and the orientation of each square was randomized on each trial. The probability of an array position being occupied was 50%, and the probability that a square was red or green was 50%. The array was present for 506 ms in no-cue trials, after which the screen turned entirely white for 47 ms (frame 4). The array then reappeared with a new element in a previously blank location. In cued conditions, after 506 ms of the static array, a pair of overlapping $1.00° \times 1.00°$ white upright squares was flashed (24 ms at 6.25° from fixation, and then 24 ms at 6.87°, no temporal blank between them) on the $\pm x$- or y-axis. The small outward apparent motion induced by this offset was included to enhance the salience of the peripheral flash. This was followed by a return to the static array for 12, 82, 153, or 447 ms, and was followed in turn by a full-screen white blank that lasted 47 ms. After the blank a new square was shown in one of 149 positions of the array (indicated by yellow circles in Fig. 1(a)) in the final frame of Fig. 1(b), representing a subset of the overall grid that fit within an imaginary 25° circle centered at fixation. The new square always appeared in a random position that had been unoccupied by a red or green square on previous frames within a given trial. Four temporal intervals or stimulus onset asynchronies (SOAs) between cue onset and new square onset were tested. Each trial could have no cue or a cue at one of four positions and one of four temporal intervals at random. On average, an abrupt onset therefore appeared at one out of four possible locations on 16 out of 17 trials, and did not appear on one out of 17 trials. There were a total of (1 (no cue) + 4 (cue positions) × 4 (SOAs)) × 149 (test positions) × 10 (trials per position) = 25,330 trials per observer in the post-practice phase of the experiment. Each of ten blocks of 2533 trials was broken down into eight sessions of 316 or 321 trials. Subjects never carried out more than ∼1500 trials on a single day. The intertrial interval was ≈3 s in order to minimize possible effects of afterimages. Data was stored and later sorted and analyzed offline.

4.5. Procedure

Observers were instructed to attend to the entire 30° diameter circular array of red and green squares and report the color of the new square in the final frame of each trial, which they indicated with a button press without feedback on the correctness of their response. Because the global flash masked the onset of the new square, detecting the new square was difficult, and required strict attention to the task. It was emphasized to observers that this new square could appear at the cued location with the same probability as at any other tested location, and that therefore there was no advantage to attending to or ignoring the cue or its location on trials that had a cue.

5. Results and discussion

This experiment was designed to answer two independent questions. One is the question addressed in this paper: Do abrupt peripheral onsets affect fixational eye movements? The other is the question of how abrupt peripheral onsets alter the distribution of visual spatial attention. Thus, two types of data were collected during this experiment: eye movement data and button-press data on the change detection task. Here we only discuss the eye movement data because the change detection data are not relevant to the question of whether abrupt onsets influence fixational eye movements. In brief, however, the change detection data revealed a marked influence of the location of the peripherally flashed spot on the distribution of correct answers, which we believe demonstrates an influence of abrupt onset location on the spatial distribution of attention. These data are described in detail elsewhere (Tse et al., 2002).

Contrary to claims that abrupt onsets and luminance increments elicit reflexive, involuntary saccades (Irwin et al., 2000), abrupt onsets did not alter observers' eye movements systematically during fixation. That is, they did not elicit systematic saccades, microsaccades, or deviations in the average pattern of fixational drift. For no observer were there significant differences between the four eye movement traces averaged respectively over the four spot locations. This was true at all four SOAs tested. The indifference of fixational eye movements to abrupt onset location or occurrence is apparent in Fig. 2. Each trace is the average of at least 700, but no more than 1490 separate trials. [2] Data was sampled every 5 ms, and a trace was made by connecting successive gaze positions. Units are degrees of visual angle. All traces are normalized to start at (0,0). The left-most column shows the average traces when there is no abrupt object onset. Among all other traces, red indicates an abrupt object onset on the positive x-axis, blue the positive y-axis, magenta the negative x-axis, and black the negative y-axis. The overlaid square indicates onset of the global array of red and green squares (frame 1 in Fig. 1(b)). This small overlaid solid square occurs 100 ms after the beginning of each trace. During these first 100 ms only the fixation point was visible against a blank background. The triangle indicates the moment of the abrupt onset (at the 605 ms position along a trace, corresponding to frame 2 in Fig. 1(b)), and the small overlaid solid diamond indicates when the new square appeared (at the 855 ms position along a trace, corresponding to frame 5 in Fig. 1(b)) to which observers responded.

Folk and colleagues (Folk & Remington, 1999; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994) formulated an 'attentional control settings hypothesis' according to which attention is only captured by an abrupt onset when it has been set to detect an abrupt luminance change. When the task involves responding to a discontinuity in color, they find that an abrupt onset does not capture attention. In contrast, Irwin et al. (2000) report that an irrelevant

[2] Note that each observer had a small but consistent "fingerprint" of drift during fixation that is visible at all SOAs and spot positions. Numerous authors have shown that there are individual differences in how observers move their eyes during a fixation task (e.g. Kowler, 1990; Nachmias, 1959, 1960; Steinman, Cushman, & Martins, 1982), but these differences have generally been discussed as statistical differences in the distribution of eye movements around the point of fixation on any given trial. Our data suggest that individual observers have a specific drift pattern that only emerges after averaging many trials, because individual trials were dominated by microsaccades in presumably random directions, and noise from potentially multiple sources, such as small head movements, eye jitter, eyeblinks, and electrical noise within our eye movement data collection system. Averaging would cancel out these sources of noise and reveal any small but characteristic underlying pattern of eye drift during fixation. The drift pattern appears to be locked to the initial onset of the array of squares, because before array onset (indicated in Fig. 2 by overlaid squares), observers were on average nearly perfect at maintaining fixation. Because the fixation spot was a 0.15° diameter disk, and the drift patterns seen here are in that range, it could be that observers maintained fixation by tracing the outline of this small disc in a consistent but idiosyncratic manner. In order to gain confidence that fixational fingerprints are robust, we would want to repeat this experiment using an eye tracker with greater spatial resolution than our video-based system. Another curious aspect of this data is that each observer consistently broke fixation by looking off in a characteristic direction upon completion of the task.

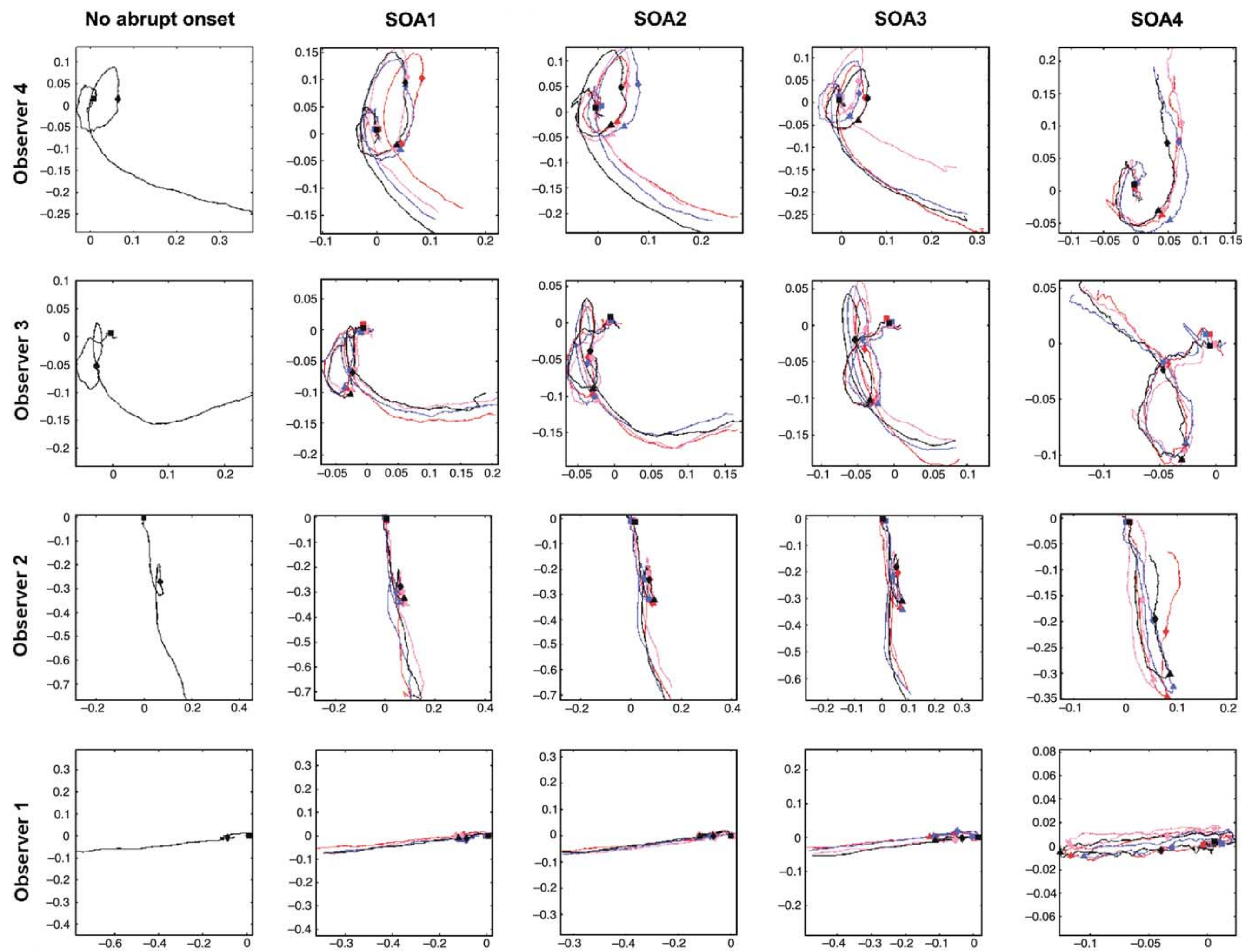

Fig. 2. Each trace is the average of 700–1400 eye movement traces recorded while observers maintained fixation. Units are degrees visual angle. All traces are normalized to start at (0,0). Red traces are averaged from trials where an abrupt onset appeared on the positive x-axis, blue, the positive y-axis, magenta, the negative x-axis, and black, the negative y-axis, except for the left-most column, where there was no abrupt onset. The overlaid square on each trace corresponds to the onset of frame 1 of Fig. 1(b), the triangle to the onset of frame 2, and the circle to the onset of frame 5.

abrupt onset captures attention even when subjects are set to search for a color singleton target. They conclude that abrupt onsets automatically capture attention, regardless of top-down attentional control settings. Even if this is true for attention, our results show that this is not true for the oculomotor system, because an abrupt onset has no influence on fixational eye movements when observers have not been preparing to saccade. Indeed, this difference suggests that the attentional and oculomotor systems can act independently, even when they usually operate cooperatively. Attention can be captured by an abrupt onset even when the oculomotor system is not captured.

Finding that an abrupt onset only triggers an automatic saccade when the visual system is preset to make a saccade is not entirely without precedent. Kowler and Steinman (1979) reported that their subjects could maintain steady fixation in the presence of a target stepping back and forth at different rates, from fixation to a location about 2° away. This involved abrupt onsets, albeit of a highly predictable kind. Similarly, Theeuwes et al. (1998, experiment 2) showed that when the location of a target is precued in advance there is no effect of its abrupt onset on eye movements. These results imply that it is the unexpectedness of an abrupt onset that captures attention and/or drives automatic saccades to the location of such an onset. Our results build on these findings and demonstrate that automatic saccadic capture is not only a function of the unexpectedness of the abrupt stimulus onset, but also a function of the prior 'set' of the oculomotor system.

6. Conclusion

We conclude that the oculomotor system operates independently of events in the visual array. Only when this system has been preset to make a saccade, can an abrupt onset bias the saccade generation process. This independence from events in the visual array is essential if the system is to have the flexibility to respond to the visual array as needed. This independence allows an observer to fixate, search, ignore, saccade to, or track events in the visual array in a flexible manner not beholden to ballistic reflex arcs, such as automatic saccades to an abrupt onset. Events in the visual array have only indirect influence on oculomotor control. If the oculomotor system were obligatorily driven by events in the visual array, animals would not be able to respond to those events in light of other needs and goals. Although the oculomotor system is particularly susceptible to abrupt onsets or luminance increments when it has been preset to saccade to a change in the visual array, it is immune to abrupt onsets when the goal at hand is to maintain fixation. The oculomotor system takes as its primary input those signals relevant to the goals of the animal, rather than raw input from the visual array. Eye movements are therefore a tool for exploring and exploiting information in the visual array in light of more general concerns and goals. The results of Irwin, Theeuwes, and colleagues (e.g. Irwin et al., 2000; Theeuwes et al., 1998, 1999) do not show that the oculomotor system is obligatorily driven by events in the visual array. They show that the system can be primed or preset to perform a certain kind of task, and that this priming of the system can lead to mistakes when an event in the visual array is sufficiently similar to the event to which the oculomotor system has been preset to make an eye movement.

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