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ENHANCING TAXI PERFORMANCE UNDER LOW VISIBILITY: ARE MOVING MAPS ENOUGH?

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We report the results of an experiment evaluating the separate and combined effects of a 3-D perspective moving map and newly developed Head-Up Display symbology on taxi performance in low visibility. Nine commercial airline pilots completed a series of gate-to-runway taxi routes at a simulated Chicago-O'Hare. Relative to a baseline condition, in which in-the-cockpit navigation support was confined to Jeppesen paper map, the 3-D moving map yielded a nonsignificant increase in taxi speed. The combination of electronic moving map and Head-Up Display yielded a considerably larger and statistically significant increase in taxi speed. These results suggest that in low visibility, Head-Up Displays can substantially improve taxi performance, over and above any improvements associated with 3-D moving maps.

INTRODUCTION

One of the primary tasks for the pilot of an aircraft is guiding the vehicle from the departure point to the correct destination. During flight, pilots of commercial glass cockpit aircraft are assisted in this task by the horizontal situation indicator (HSI) display. If the aircraft is equipped with a Head-Up Display (HUD), additional assistance is available in the form of the flight director symbology. As currently engineered, however, neither the HSI nor the HUD symbology support navigation on the airport surface. Pilots are forced to rely on paper maps and the information available in the out-the-window (OTW) scene. Wayfinding using paper maps is a highly demanding task (Aretz, 1991), particularly at large, complex airports (Andre, 1995). Wayfinding difficulty increases still further under low visibility conditions, as OTW information becomes degraded or unavailable.

The difficulty of ground taxi under low visibility conditions poses a significant challenge to the efficiency of the national airspace system (Foyle, Andre, McCann, Begault, Wenzel, & Battiste, 1996). There are two reasons for this. First, because ground taxi is so reliant on OTW information, most airports cease operations when visibility goes below a minimum value. With today’s tight operating schedules, a shutdown at even a single airport has a ripple effect that impacts negatively on schedules nationwide. Second, even if visibility doesn’t deteriorate all the way to the minimum, pilots taxi more slowly, and make more navigation errors, than in clear-weather conditions (McCann, Foyle, Andre, & Battiste, 1996). Thus, there is an urgent need to develop displays to help pilots taxi efficiently in low visibility.

Electronic moving-map displays

Recent advances in computer processing power, combined with widespread access to accurate real-time calculation of aircraft position (i.e., via GPS technology) have enabled the development of electronic moving map (EMM) displays. The typical EMM depicts the location of the aircraft on the airport surface and updates the location in real time. If the EMM features graphical route guidance, a quick glance at the display is sufficient to assess the current position of the aircraft relative to the cleared route. Furthermore, by rotating the map so that it is always aligned with the current heading of the aircraft, the EMM removes the need to cognitively "align" ego-referenced information in the OTW scene with the world-referenced information on standard paper maps (Aretz, 1991). Thus, not only does an EMM supply information useful for ground taxi, it does so in a form that reduces the information processing demands on the pilot (Battiste, Downs, & McCann, 1996; McCann et al., 1996).

A number of studies have examined the effects of EMMs on ground taxi performance in medium- to high-fidelity simulation (Batson, Harris, & Hunt, 1994; Battiste et al., 1996; McCann et al., 1996; Tu & Andre, 1996; Zimmerman, 1994). The results are straightforward: Pilots make fewer navigation errors, and taxi at a greater speed, when an EMM is available. These performance benefits are greater when graphical route guidance is featured (Battiste et

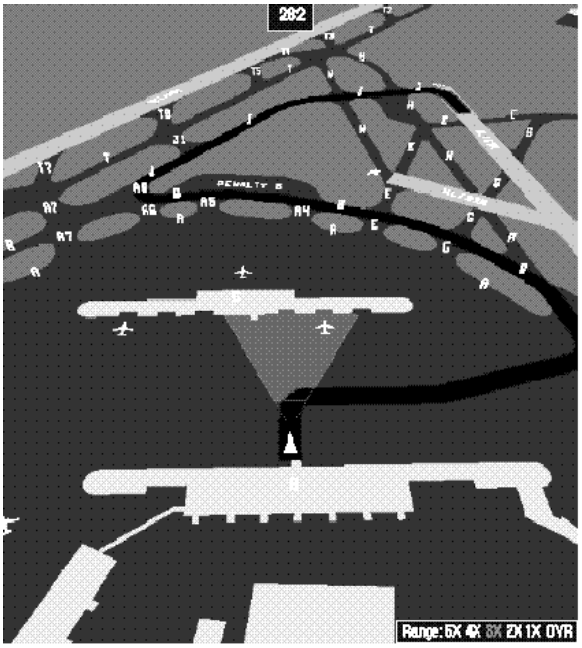

Figure 1. Electronic Moving Map, showing the ownship about to proceed from Concourse B and follow a cleared route to Runway 9L at Chicago O'Hare. The triangle represented the center of gravity of the ownship, and the light triangular area in front represented the pilot's actual visual field (i.e., the area visible out the window). Route guidance was provided by the darkened area (actually magenta). Note the menu of zoom levels in the bottom right hand corner of the display; these were self-selectable.

al., 1996; Tu & Andre, 1996) and more notable in low than in high visibility (Battiste et al., 1996; McCann et al., 1996).

In spite of these performance benefits, EMMs are not without their drawbacks. The typical EMM provides only a 2-D plan view of the airport surface. This display format occupies a “world-centered” reference frame, quite dissimilar to the “ego-centered” reference frame of the OTW scene (Wickens & Prevett, 1995). As a result, pilots must perform a variety of cognitive operations to bring the EMM reference frame into alignment with the OTW frame (Aretz, 1991). These operations are both effortfull and time consuming.

Recognizing the problem, a number of researchers have attempted to bring the reference frames of the EMM and the OTW scene into closer alignment by designing a 3-D perspective EMM (Mejdal & Andre, 1996; Tu & Andre, 1996; Wickens & Prevett, 1995). For example, the EMM designed by Andre and his associates (Figure 1) has higher resolution in the area closest to the aircraft. This results in a more natural, ecological representation of the airport environment than a conventional 2-D display. In a part-task taxi simulation, Tu and Andre (1996) compared taxiing behavior between a standard 2-D perspective EMM and the 3-D perspective EMM. Pilots overwhelmingly preferred the 3-D display, consistent with the hypothesis that such a display design reduces the cognitive effort involved in aligning the EMM representation with the OTW view.

Unfortunately, despite the strong preference for the 3-D version, it was associated with slightly slower taxi speeds than the 2-D version. Similarly, Lasswell and Wickens (1995) found that pilots taxied significantly more slowly with a 3-D compared to a 2-D version of a route guidance display. Why would 3-D displays yield slower taxi speeds? One possibility, discussed by Lasswell and Wickens, stems from the fact that their 3-D display provided a shorter view of the forward route than the 2-D display. As a result, pilots had fewer “look ahead” cues that might help maximize forward taxi speed (see also Foyle et al., 1996). For example, if the pilot knows that the current section of the cleared route is a long straightaway, he or she might be willing to taxi more rapidly through the straight segment, compared to when the length of the current straightaway is not known with certainty.

This explanation may apply to the Tu and Andre (1996) results as well. Their pilots typically selected a higher zoom level for the 3-D display than the 2-D display. The higher the zoom level, the less preview of the forward route is available.

HUD symbology for taxi

If pilots taxi more slowly with a 3-D EMM because of the tendency to select a high zoom level, one way to recover forward speed might be to combine the EMM with a display that restores the missing “look-ahead” cues. A promising candidate is a HUD-based taxi display developed recently by NASA-Ames researchers (Foyle et al., 1996). Shown in Figure 2, the HUD symbology includes a series of evenly-spaced tiles overlaying the taxiway centerline, and a regularly-spaced series of cones stretching along each side of the cleared taxiway. These symbols are "scene-linked" such that, as the aircraft taxies through the environment, the symbols undergo the same optical transformations they would if they were actual objects placed along the taxiway. Among other features, this symbology supplies highly salient “look ahead” cues. For example, in a long straight section, the symbology highlights the cleared route out to distance of 1000 ft; as the plane approaches the next turn segment, the symbology curves to conform with the curvature of the turn. This alerts the pilot to the distance remaining to the curve, and how severe the turn angle will be. Thus, the symbology can be used to optimize forward speed decisions, such as what maximum speed can be safely achieved on the straightaway segment, and when deceleration into the curve should commence.

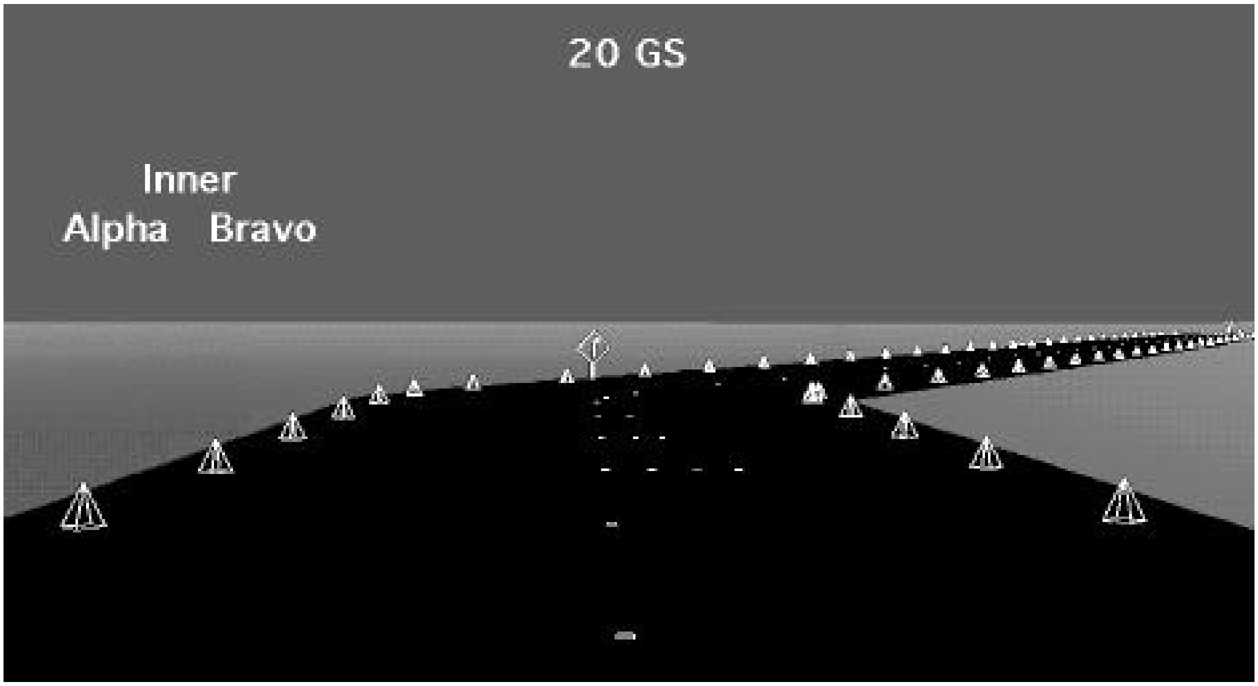

Figure 2. Depiction of HUD taxi symbology over a generic taxiway. All HUD symbology shown in white (actually green).

The present study

Assume that the availability of "look ahead" cues is important for maximizing forward speed in low visibility. Suppose further that pilots generally select high zoom levels for 3-D EMMs, thereby removing "look-ahead" cues from the display. Since these cues are available on the HUD, we would expect the combination of scene-linked HUD symbology and 3-D EMM to yield an increase in forward taxi speed, compared to an EMM-alone condition. The primary purpose of the present simulation was to test this hypothesis. Airline pilots completed a series of gate-to-runway departure routes at Chicago O'Hare airport. Each pilot's performance was evaluated under a baseline condition (in which navigation support was limited to a Jeppesen paper map of O'Hare and the standard OTW cues); an EMM-alone condition (where the baseline navigation support was augmented by a 3-D perspective EMM); and an EMM + HUD condition (where the baseline navigation support was augmented by a 3-D perspective EMM and HUD taxi symbology).

METHOD

Participants

Nine highly-experienced male airline pilots participated in the study.

The simulation

The out-the-window visual scene, a high fidelity rendering of Chicago O'Hare, was driven by an SGI Onyx Reality Engine 2, rear-projected on an Electrohome screen measuring 2.43 m (width) by 1.83 m (height). The HUD consisted of a semi-transparent silvered glass sheet (combiner). HUD symbology was generated by an SGI Personal IRIS, projected through a Fresnel lens, and reflected into the participants' eyes through the combiner glass. All symbology was green and appeared at a focal distance of 2.43 m, the same optical distance as the distance between the participant and the wide screen.

The EMM (Figure 1) was displayed on a 23-cm diagonal CRT located below and to the left of the participant at a distance of approximately 1 m. The display consisted of a 3-D perspective depiction of Chicago O'Hare that could be viewed at one of five zoom levels. Route guidance was provided by a magenta "ribbon" aligned with the cleared route.

The vehicle model used in the simulation emulated the handling characteristics of a B737. Vehicle control was accomplished via inputs to rudder and toe brakes, a throttle, and a nose-wheel tiller.

Design

The experiment contained 24 trials, each consisting of a specified route that began in a ramp area adjacent to a

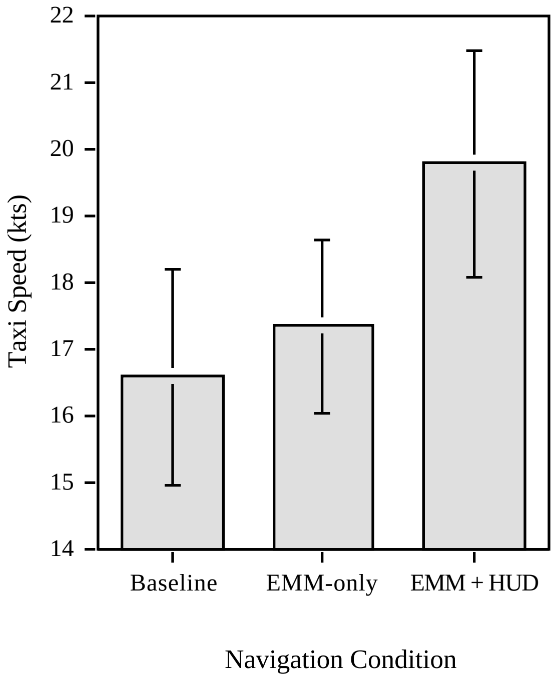

Figure 3. Mean forward taxi speed as a function of navigation condition.

terminal, and finished when the airplane turned onto the departure runway. The routes averaged 2 nmi in length and took approximately 7 min to complete. The assignment of routes to trials was random, and the same random order was maintained for each participant.

The experiment was divided into three blocks of 8 trials (the first trial in each block was considered practice). In the baseline block the only navigation aid provided was a Jeppesen paper map of Chicago O'Hare. In the EMM block, pilots were provided with the paper map and the EMM; in the EMM + HUD block, pilots were provided with the paper map and both the EMM and the HUD taxi symbology. Block order was fully counterbalanced. All trials were performed in low visibility conditions (RVR 700 ft).

Procedure

At the beginning of each trial, the experimenter asked the participant whether he was ready via an intercom. Following the "ready" acknowledgment, a written clearance appeared to the left of the EMM (the clearance appeared regardless of whether the EMM itself was present). The experimenter repeated the clearance verbally, and solicited a "clearance received and understood" acknowledgment from the pilot. The pilot then taxied along the cleared route to the departure runway, at which point the forward screen went blank. The experimenter then initiated the next trial.

Performance measures

Forward taxi speed was sampled at a rate of 2 Hz. These speeds were then averaged to arrive at a mean taxi speed for each trial. Although the main focus of this study was on taxi speed, we were also interested in the effect of the EMM and HUD symbology on navigation accuracy. To evaluate route following accuracy, the experimenter kept a numeric count of each time that the participant guided the aircraft off the cleared route. This number was then summed across the 7 experimental trials in each block (condition).

RESULTS

Choice of zoom level

Of the five possible zoom levels, the pilots set the EMM to level 5 (highest possible) 26% of the time, and to level 4 57% of the time. Thus, as in Tu and Andre’s (1996) study, there was a strong preference for high zoom levels.

Forward speed

Mean forward speed across the 7 experimental trials in the baseline, EMM-alone, and EMM + HUD conditions is plotted in Figure 3. As shown in the figure, the EMM-alone condition yielded a modest 0.76 kt increase in taxiing speed relative to the baseline (paper map) condition. The increase was substantially greater (3.2 kts) in the EMM + HUD condition. A repeated-measures analysis of variance revealed a highly significant effect of navigation condition, $F(2,16) = 8.8$, $p < .01$. Paired comparisons showed that the EMM+ HUD condition differed significantly from both the baseline ($t(8) = -3.59$, $p < .01$), and EMM-alone ($t(8) = -3.53$, $p < .01$) conditions. The difference between the baseline and EMM-alone conditions was not reliable, $t(8) = -.94$.

Accuracy

Over the course of seven departure routes, subjects made an average of 2.3 errors in the baseline condition, 1.0 error in the EMM-alone condition, and only 0.1 error in the EMM + HUD condition. Once again, the effect of navigation condition was highly significant, $F(2,16) = 10.31$, $p < .01$. Paired comparisons revealed that each condition differed reliably from the others.

DISCUSSION

Taxiing in low visibility is both slow and error-prone (McCann et al., 1996). Previous work has found that EMMs improve ground taxi performance, particularly under low visibility. Perspective (i.e., 3-D) displays are an attractive design option for such maps. The 3-D feature minimizes the effort necessary to mentally “align” the EMM information with the ego-referenced OTW view, and pilots have expressed a clear preference for 3-D over 2-D designs. However, studies have revealed a potential human factors drawback to the 3-D option. Compared to the standard 2-D display, pilots tend to adopt a higher zoom level, which removes look-ahead cues that may be useful for maintaining an optimum level of forward taxi speed. Following Lasswell and Wickens (1995), this might explain the consistent finding of slower taxi speeds with 3-D compared to 2-D displays (Tu & Andre, 1995; Lasswell & Wickens, 1995).

In the present experiment, pilots selected the highest or next-to-highest zoom levels 83% of the time. The presence of virtual or "scene-linked" HUD symbology, which provides a better set of “look ahead” cues than a “zoomed-in” EMM, yielded a substantial forward speed increase over and above the increase found with the EMM alone. This finding has both human factors and practical implications. From a human factors perspective, the result suggests that any individual display likely contains a mix of positive and negative features. Optimal enhancement of operator performance may well require a set of displays that complement each other’s strengths and weaknesses. In the present case, 3-D EMMs support navigation awareness, as reflected by the reduction in navigation errors in their presence. However, the tendency for pilots to select high zoom levels removes look-ahead cues useful for maximizing forward speed. The scene-linked HUD symbology yielded a dramatic increase in forward speed relative to the EMM-alone condition, possibly because the HUD symbology restored the critical “look-ahead” cues.

At a practical level, the performance improvements associated with the combination of EMM and HUD may be large enough to impact both airline schedules and fuel costs significantly. However, achieving these performance improvements requires both forms of display; an EMM alone is not sufficient.

ACKNOWLEDGMENTS

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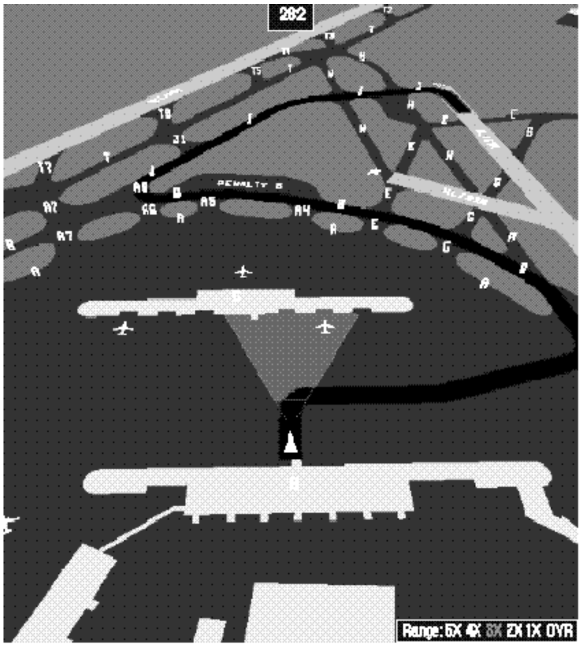

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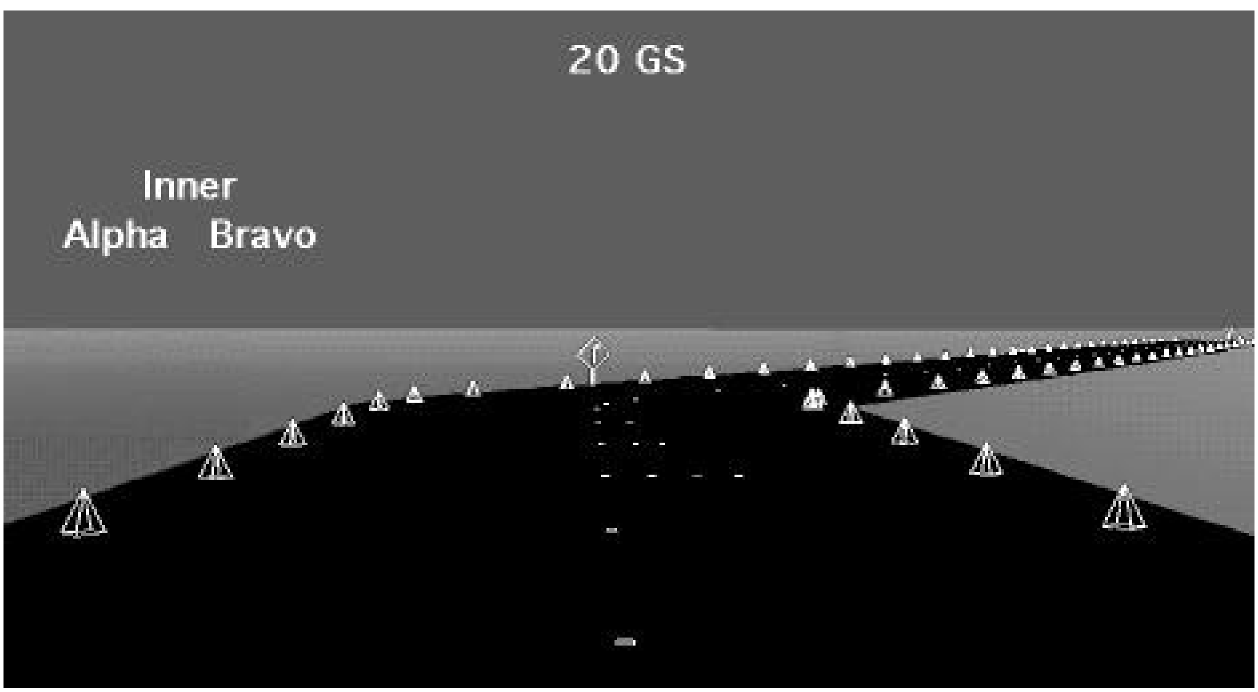

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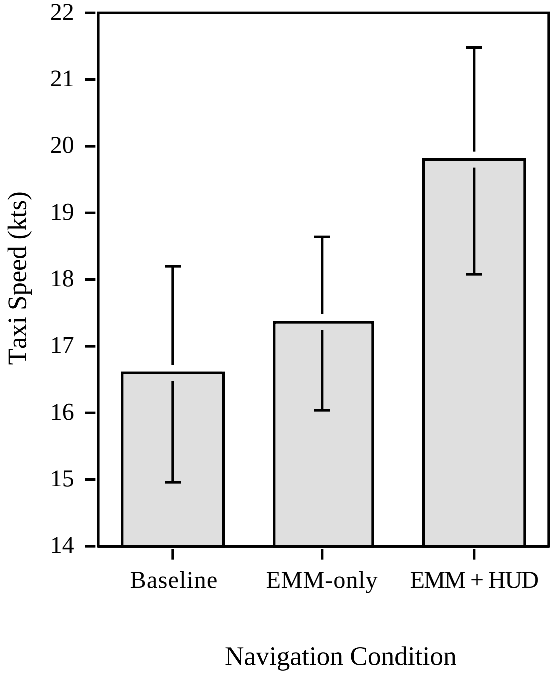

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