Human Factors in Design, Engineering, and Computing, Vol. 238, 2026, 2249–2259
https://doi.org/10.54941/ahfe1008451

Perceived Walking Duration Across Street-tree Spatial Patterns: Toward a Route Recommendation System

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ABSTRACT

Walking-route recommendations prioritize distance and travel duration, but streetscape differences can affect the perceived walking duration even on routes with similar travel times. Accounting for this variation could support recommendations tailored to walking experience; however, the relationship between perceived walking duration and streetscape structure remains unclear. In this study, we investigate how tree density and spacing regularity are related to perceived walking duration. We conducted a virtual reality walking experiment with 21 participants in six streetscapes combining three tree density levels with regular or irregular spacing. Coniferous or broadleaf tree shapes were assigned between participants. After each trial, the participants reported the perceived walking duration, and eye-tracking data and first-person HMD-view videos were recorded. After excluding a single outlier, 120 trials from 20 participants were analyzed. Linear mixed-effects models related the duration estimation error, i.e., the difference between the perceived and actual walking duration, to the tree layout conditions. The results showed that walking duration was perceived as longer with increasing tree density. For broadleaf trees, the duration tended to be perceived as shorter under regular spacing than irregular spacing. Correlation and cluster analyses showed that longer mean fixation durations on street trees accompanied longer estimates in the tree-focused and scene-exploration clusters (but not the road-focused cluster). Video features quantified visible streetscape elements. Edge-pixel measures captured density, and ACF- and FFT-based measures captured spacing regularity; however, neither explained the variation in the walking duration estimation error. The findings indicate that walking-route recommendations based on perceived walking duration should consider streetscape structure and user-specific gaze behavior.

Keywords: Perceived walking time, Street trees, Eye tracking, Virtual reality walking, Route recommendation

INTRODUCTION

Generally, walking-route recommendations prioritize measurable route attributes, e.g., distance and travel time. However, walking experiences are also shaped by the streetscape characteristics perceived by pedestrians (Ewing and Handy, 2009). Route recommendation methods that consider various qualities, e.g., beauty and quietness, have also been proposed (Quercia et al., 2014), extending route selection beyond basic travel efficiency. Furthermore, routes with equal travel time may differ in perceived walking time. Perceived

Received September 25, 2026; Revised October 22, 2026; Accepted November 2, 2026; Available online December 1, 2026

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walking time could support route recommendations tailored to the intended walking experience, e.g., shorter-feeling routes for time-conscious travel and longer-feeling routes for leisurely walking.

Previous studies on time perception have shown that subjective duration does not always correspond to elapsed time and can vary with stimulus changes and attentional allocation (Block and Zakay, 1997; Fraisse, 1984; Tse et al., 2004). For example, during walking, streetscape elements continuously enter pedestrians' visual fields, and their appearance and arrangement may influence which objects pedestrians attend to. In addition, gaze behavior is related to scene understanding and visual information processing (Henderson and Hollingworth, 1999). An eye-tracking study examined the relationship between streetscape elements and perceived walking time (Wang and Zhang, 2025). These findings suggest that perceived walking time may be related not only to the types of streetscape elements but also their arrangement and pedestrians' attentional allocation.

Field experiments have shown that walking duration estimates differ among urban paths with different spatial configurations (Isaacs, 2001). Trees are common natural elements in urban walking environments, and increasing the number of trees in residential street images has been shown to increase restoration likelihood ratings (Lindal and Hartig, 2015). Natural scenes may also produce longer duration estimates than built scenes (Davydenko and Peetz, 2017). However, previous studies have primarily examined overall street configurations, the quantity of visible greenery in a streetscape, or comparisons of entire scenes categorized as natural or built. Thus, the relationship between perceived walking time and spatial properties, e.g., the number and spacing of street trees, remains underexplored.

Both street-tree density and spacing regularity vary; therefore, the amount and repetition of visual elements encountered during walking also vary. To compare streetscapes with different roadside elements using common measures, the amount and repetition of elements visible from the pedestrian's perspective can be quantified over time. However, even under the same layout, the visual information acquired by pedestrians can differ depending on what they view and how long they continue viewing each object. Thus, gaze behavior provides complementary information that can support investigating the relationship between layout conditions and perceived walking time.

In this study, a virtual reality (VR) walking experiment was conducted to investigate how street-tree density and spacing regularity are related to perceived walking time. We also examined whether the participants' viewing behavior and continuous measures of streetscape structure are associated with the difference between perceived and actual walking time. Collectively, the findings of these analyses provide evidence for walking-route recommendations that consider perceived time.

VR WALKING EXPERIMENT

Experimental Design

The experiment examined how street-tree density and spacing regularity are related to the difference between perceived and actual walking time. Here, 21 undergraduate and graduate students participated in the experiment (16 men

and five women; mean age = 22.4 years, standard deviation (SD) = 0.72). Figure 1 shows the experimental setup and street-tree layout conditions. As shown in Figure 1B, we combined three levels of street-tree density with two levels of spacing regularity, for a total of six conditions. Note that both factors varied within participants. The low-, medium-, and high-density conditions contained four, eight, and 16 trees per 100 m on one side of the street, respectively. Under the regular spacing condition, the corresponding tree intervals were 25.0, 12.5, and 6.25 m. Under irregular spacing, each tree was shifted along the walking direction from its corresponding regular position by a random offset within ±50% of the regular interval (without changing the number of trees at each density). Two types of street trees were presented, e.g., coniferous and broadleaf, to evaluate whether the relationship between the layout conditions and perceived walking time was consistent across tree shapes. Here, tree shape was a between-participants factor, with 11 and 10 participants assigned to the coniferous and broadleaf conditions, respectively. Each participant completed one trial in each of the six layout conditions with the assigned tree shape.

The actual walking time had six levels, i.e., 250, 270, 290, 310, 330, and 350 s. For each participant, a different duration was assigned to each of the six layout conditions, and each duration was experienced once. At a constant walking speed, these durations corresponded to different travel distances through the virtual street. Note that the condition order and duration-to-condition assignment were counterbalanced across participants using a Latin square design.

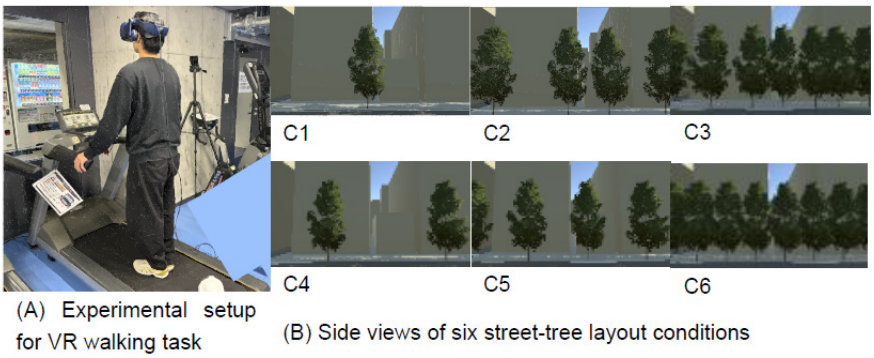


Figure 1: Overview of VR walking experiment. In panel B, C1–C3 show irregular spacing at low, medium, and high density, and C4, C5, and C6 show regular spacing at the same densities as C1, C2, and C3, respectively.

METHOD

During the experiment, the participants wore a head-mounted display (HMD; HTC VIVE Pro Eye) and walked on a treadmill at a fixed speed of 4 km/h (Figure 1A). A virtual street developed in Unity 2022.3.62f1 was presented through the HMD. Here, the viewpoint in the virtual environment changed according to the position and orientation of each participant's head.

Prior to the main experiment, the participants completed a practice trial to become familiar with the HMD device, treadmill walking, and

reporting procedure. In each experimental trial, the experimenter started the VR presentation and treadmill simultaneously, and both were stopped when the assigned walking duration had elapsed. In addition, white noise was played through the HMD's integrated headphones during walking to reduce the influence of ambient sounds. Each participant completed six trials, with an approximately 1-min rest between trials to reduce fatigue. After each trial, the participants reported the perceived walking duration in seconds. During walking, the HMD's built-in eye tracker logged gaze direction and the virtual object intersected by a ray projected in that direction. The first-person view displayed through the HMD, reflecting each participant's head position and orientation, was also recorded.

RESULTS

Perceived Walking Time

In this study, the difference between the perceived and actual walking duration was defined as time estimation error (perceived walking time – actual walking time). Here, positive and negative values indicated that the estimated walking duration was longer and shorter than the actual duration, respectively. The Smirnov–Grubbs test was applied separately within the coniferous and broadleaf conditions to each participant's mean time estimation error. One participant in the coniferous condition was identified as an outlier. This participant was excluded, leaving 20 participants (10 in each tree-shape condition), and 120 trials were used for analysis. Figure 2 shows the time estimation errors by layout conditions.

Mean time estimation errors were −31.5 s, −27.6 s, and −8.0 s in the low-, medium-, and high-density conditions, respectively. Under the high-density condition, the mean was closer to zero, indicating less underestimation than in the low- and medium-density conditions. To account for repeated measurements within participants and individual differences, a random intercept for participant was included in a linear mixed-effects model. Here, street-tree density, spacing regularity, tree shape, and their interactions were included as fixed effects, with the actual walking duration as a covariate. The contribution of each fixed effect was evaluated using likelihood-ratio (LR) tests that compared models with and without the corresponding effect.

An overall effect of street-tree density was detected (LR $\chi^2(2) = 7.323$, $p < 0.05$). To account for the three pairwise comparisons among density levels, the p values were adjusted using Holm's method, and none remained significant (all adjusted $p \geq 0.135$). Under the coniferous condition, mean time estimation errors were −18.8 s and −15.3 s under the irregular and regular spacing conditions, respectively, with no significant difference ($p = 0.636$). Under the broadleaf condition, the mean error was −14.0 s and −41.3 s under the irregular and regular spacing conditions, respectively. The walking duration was estimated as shorter under regular spacing; however, this within-condition comparison did not reach the 5% significance level ($p = 0.055$). The linear mixed-effects model showed no main effect of spacing regularity (LR $\chi^2(1) = 0.496$, $p = 0.481$) or tree

shape (LR $\chi^2(1) = 0.235$, $p = 0.628$). An interaction between tree shapes and spacing regularity was detected (LR $\chi^2(1) = 4.259$, $p < 0.05$). The interactions between tree shapes and street-tree density, between street-tree density and spacing regularity, and among all three factors were not significant (all $p \geq 0.296$).

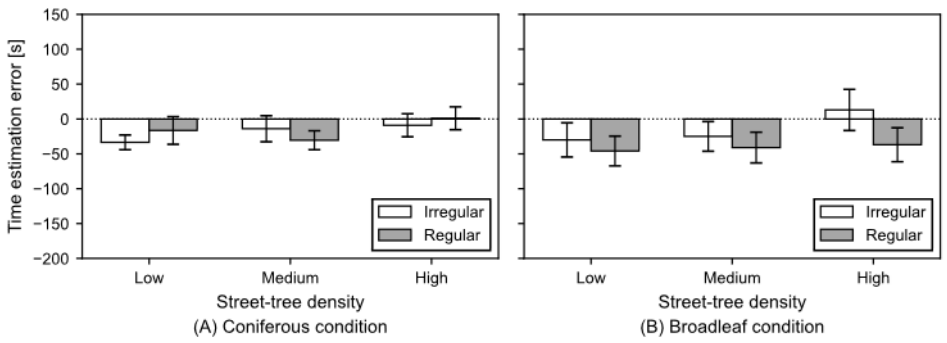


Figure 2: Mean time estimation error under irregular and regular spacing at each street-tree density level. Error bars indicate *SD*.

The street-tree density exhibited an overall effect; however, no specific pair of density levels differed significantly. The relationship between spacing regularity and time estimation error differed between the two tree shapes.

Street-Tree Fixation

The analysis showed that the relationship between layout conditions and time estimation error varied by tree shape. Even under the same layout condition, the participants may have viewed different objects. Thus, we analyzed fixation targets and fixation durations during walking to investigate the factors associated with variation in time estimation error not captured by the layout conditions.

Here, the I-DT algorithm (Salvucci and Goldberg, 2000) was applied to the gaze logs. A fixation was defined as gaze positions remaining within a 75-pixel dispersion threshold for at least 100 ms. Each fixation was classified as a street tree, the road, or another object according to the virtual object intersected by the gaze ray in Unity. Seven gaze measures were calculated for each trial: the proportions of fixation time directed to street trees, the road, and other objects; mean fixation durations on street trees and the road; the number of switches between fixation targets; and the number of returns to street trees after fixating on another target. The relationship between each measure and time estimation error was examined using Spearman's rank correlation coefficient.

The mean fixation duration on street trees was positively correlated with time estimation error ($\rho = 0.222$, $p < 0.05$). Figure 3 shows that trials with longer individual fixations on street trees tended to exhibit longer walking duration estimates. Note that none of the other six measures was significantly correlated with time estimation error (all $p \geq 0.201$).

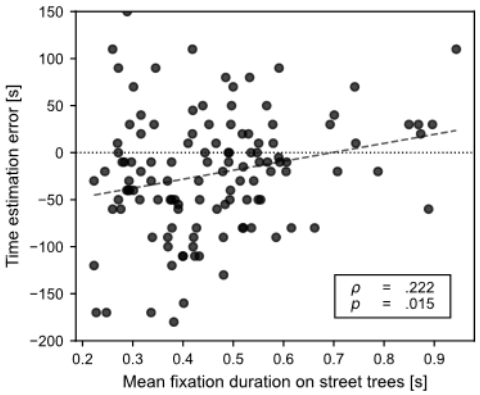


Figure 3: Relationship between mean fixation duration on street trees and time estimation error across 120 trials. Each point represents one trial, and the dashed line shows a fitted linear trend for visualization. ρ denotes Spearman's rank correlation coefficient, and p denotes the corresponding p value.

To determine whether this correlation reflected within-participant changes or between-participant differences, the mean fixation duration on street trees was divided into two components. Here, the within-participant component represented the deviation of each trial from the participant's own mean, and the between-participant component represented each participant's mean. The linear mixed-effects model included a random intercept for participant, with the within-participant component, the between-participant component, actual walking duration, and tree shape as fixed effects. The within-participant component exhibited a positive coefficient; however, it was not significantly related to time estimation error ($\beta = 6.288$ s/SD, 95% CI [−1.430, 14.006], $p = 0.110$). The between-participant component was also not significantly related to time estimation error ($\beta = 13.222$ s/SD, 95% CI [−8.039, 34.483], $p = 0.223$).

For the two tree-shape conditions, separate Spearman correlations showed no significant relationship under the coniferous condition ($\rho = -0.053$, $p = 0.689$). Under the broadleaf condition, the participants tended to estimate walking duration as longer relative to the actual duration in the trials with longer mean fixation durations on street trees ($\rho = 0.434$, $p < 0.01$). However, neither the within-participant nor the between-participant coefficient was significant in the mixed-effects model. In addition, the model showed no interaction between the mean fixation duration on street trees and tree shape (LR $\chi^2(1) = 0.323$, $p = 0.570$). Thus, this tendency was not confirmed to differ between the coniferous and broadleaf conditions.

Participant Gaze Behavior

To capture differences in how the participants viewed the streetscape, they were classified using six out of the seven aforementioned gaze behavior measures, i.e., street-tree gaze proportion, road gaze proportion, mean fixation duration on street trees, mean fixation duration on the road, the number of switches between fixation targets, and the number of returns to street trees

after fixating on another target. Here, the gaze proportion on other objects was excluded because the three gaze proportions summed to one, making its allocation information redundant. For each measure, the mean across the six trials was calculated for each participant, and the resulting participant-level means were standardized to a mean and SD of 0 and 1, respectively. Then, Ward's hierarchical clustering (Ward, 1963) was applied, where the number of clusters was set to three based on the linkage distances in the dendrogram and cluster interpretability.

The tree-focused cluster included five participants and exhibited a high street-tree gaze proportion and few switches between fixation targets. The scene-exploration cluster included six participants who viewed both street trees and the road and frequently returned to street trees after fixing their gaze on another target. The road-focused cluster included nine participants and exhibited a high road gaze proportion, frequent switches, and a low street-tree gaze proportion.

A linear mixed-effects model included a random intercept for participant, with cluster, actual walking duration, and tree shape as fixed effects. Here, the mean time estimation error did not differ significantly among the clusters (LR $\chi^2(2) = 1.000$, $p = 0.607$), indicating that the clustering results did not directly distinguish participants who estimated walking duration as longer from those who estimated it as shorter. Spearman correlations between the mean fixation duration on street trees and time estimation error were calculated for each cluster. Positive correlations were found in the tree-focused ($\rho = 0.590$, $p < 0.001$) and scene-exploration ($\rho = 0.643$, $p < 0.001$) clusters. No significant correlation was found in the road-focused cluster ($\rho = -0.150$, $p = 0.280$).

The linear mixed-effects model showed no interaction between the within-participant component of the mean fixation duration on street trees and cluster (LR $\chi^2(2) = 0.484$, $p = 0.785$). In both the tree-focused and scene-exploration clusters, the participants tended to estimate walking duration as longer relative to the actual duration in the trials with longer mean fixation durations on street trees. However, the interaction analysis did not confirm that this tendency differed among the clusters.

DISCUSSION

Individual Differences in Perceived Walking Duration

The time estimation error varied among the participants even when they experienced the same street-tree layout, which indicates that responses to the layout conditions were not uniform among the participants. The mean estimates were shorter than the actual walking duration under all three density conditions, with less underestimation at higher densities. However, after Holm adjustment, no specific pair of density levels differed significantly. The layout conditions alone were insufficient to predict perceived walking duration consistently across participants.

The relationship with spacing regularity also differed by tree shapes. Under the broadleaf-tree condition, the participants tended to estimate the walking duration as shorter under the regular spacing condition. The wider

crowns of broadleaf trees may have made the repetition of trees and the visual continuity of the streetscape more noticeable. Such visual repetition may have been related to the estimation of the walking duration. However, this perceptual process was not measured directly in this study; thus, further investigation is required.

Furthermore, the street-tree gaze proportion was not significantly related to the walking duration estimation error, whereas the mean fixation duration on street trees exhibited a positive relationship in the correlation analysis. This indicates that the duration of each fixation may be more relevant to perceived walking duration than the total time spent looking at street trees.

The mean duration estimation error did not differ among the gaze-behavior clusters. However, the tendency to estimate longer walking durations in trials with longer mean fixations appeared in both the tree-focused and scene-exploration clusters but not in the road-focused cluster. It also appeared under the broadleaf condition but not under the coniferous condition. The mixed-effects analyses did not confirm that this tendency differed by cluster or tree shape. Thus, the mean fixation duration may help characterize individual variation not represented by the gaze proportion or cluster membership. Although these results do not establish that fixation behavior caused changes in the perceived walking duration, the recurring tendency across the overall, tree shape–specific, and cluster-specific analyses supports mean fixation duration as a candidate measure to characterize user-specific variation in perceived walking duration.

Quantifying Spatial Patterns

In this study, the low-, medium-, and high-density conditions and irregular and regular spacing conditions were specifically defined for this experiment and cannot be applied directly to other streets. To compare spatial layouts using continuous measures, the visual changes presented during walking were analyzed using first-person recordings from 18 participants and 108 trials. The recorded view was sampled at 1-s intervals.

Here, the density-related measures were the within-trial mean and SD of the proportion of pixels detected as edges using the Canny method (Canny, 1986). These measures represented the average amount of visible boundaries and their temporal variation during walking. The regularity-related measures included the peak of the autocorrelation function (ACF; Box et al., 2015) calculated from the time series of vertical-edge values and the dominant-frequency power ratio obtained using fast Fourier transform (FFT) (Cooley and Tukey, 1965). The ACF peak represented the strength with which visual changes recurred at a consistent time interval. The dominant-frequency power ratio was calculated by dividing the maximum spectral power within the search band by the total power across all frequency components (except the direct current component). Here, a higher value indicates that a larger proportion of the visual changes recurred at a consistent interval, representing greater temporal regularity.

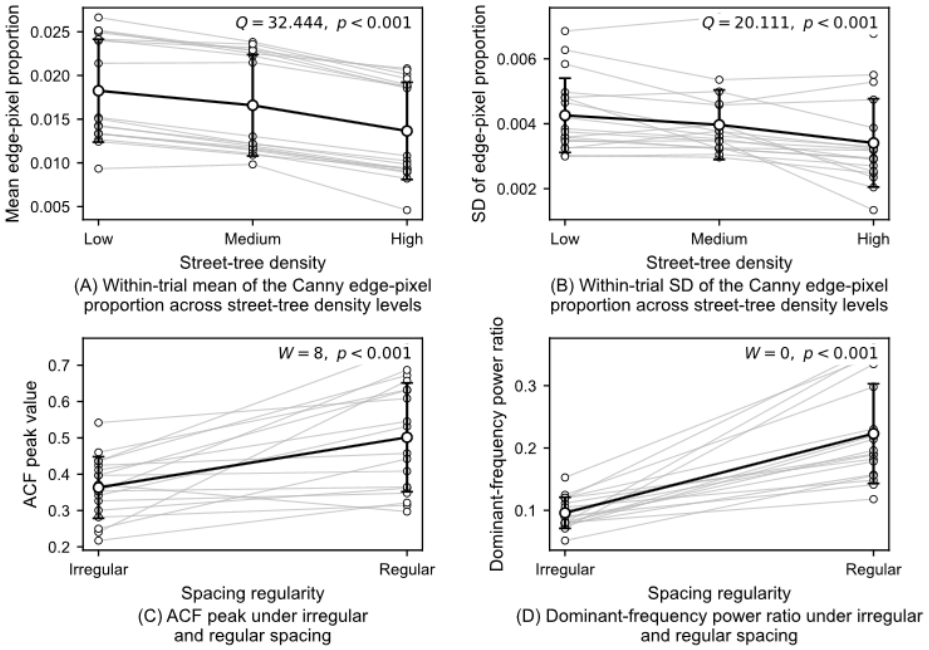


Figure 4: Visual measures of street-tree density and spacing regularity derived from first-person HMD-view videos recorded during walking. The values for each participant were averaged across levels of the other layout factor. Gray lines and open circles represent participant-level means. Black points and lines represent group means, and error bars indicate ±1 *SD* across participants. *Q* denotes the Friedman test statistic (panels A and B), and *W* denotes the Wilcoxon signed-rank test statistic (panels C and D).

Figure 4 shows the four visual measures across the street-tree density and spacing-regularity conditions. As shown, the mean and *SD* of the edge-pixel proportion decreased as street-tree density increased. Under the high-density condition, overlapping tree crowns and foliage may have obscured the boundaries between the trees, sky, and background, potentially producing larger continuous regions. The ACF peak and dominant-frequency power ratio were higher under the regular spacing condition. These measures reflected the repeated visual changes produced by the street-tree layouts. In addition, the recurrence periods detected by the ACF and FFT corresponded to the expected tree-passing periods under the low- and medium-density conditions; however, this correspondence was weaker under the high-density condition. These results indicate a limitation in applying these measures to densely planted layouts.

The linear mixed-effects models accounting for participant differences, actual walking duration, and tree shape showed that none of the four visual measures explained the variation in the walking duration estimation error. Collectively, these results indicate that continuous visual measures derived from the first-person recordings can characterize streetscape structure but cannot explain perceived walking duration by themselves. Nevertheless, such measures may provide a common basis to compare recurring spatial patterns across streets.

Implications for Route Recommendation

Perceived walking duration could be incorporated into route recommendation systems to identify routes that are likely to feel shorter or longer among routes with similar actual travel times. However, the responses to street-tree layouts varied among participants; thus, it is difficult to recommend a particular route based on streetscape structure alone. Route recommendation should consider both the streetscape structure and user-specific responses.

The visual measures examined in this study captured differences in street-tree density and spacing regularity and may provide common measures to compare streetscape structure across routes. Thus, future studies should investigate whether these measures also capture the structure of other streetscape elements, e.g., buildings and signs, and whether the current findings apply to real-world street environments. In addition, route recommendation based on perceived walking duration will require combining these structural measures with the types of elements present along each route and user-specific response patterns.

CONCLUSION

The findings of this study indicate that the relationship between street-tree layout and perceived walking time was not uniform and should be considered in relation to both tree shape and how users view the streetscape. In particular, the mean fixation duration on street trees (rather than the street-tree gaze proportion) may help characterize individual differences in perceived walking duration. In addition, visual measures derived from first-person recordings characterized street-tree density and spacing regularity; however, these measures alone could not explain the differences in the perceived walking duration. Thus, route recommendation based on perceived walking duration should combine quantitative descriptions of streetscape structure with user-specific gaze behavior.

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