Effect of Data Visualization on Users' Running Performance on Treadmill

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Abstract: This paper examined how real-time data visualization influences treadmill users' performance and experience. Traditional treadmill displays are often represented with texts, limiting user engagement and motivation. By applying visualization techniques that align with human cognitive processing, such as line charts and progress indicators, we proposed data visualization designs to represent running performance metrics more meaningfully. The study applied 3 display conditions: traditional and two improved visualization displays. Through a within-subjects experiment with 18 participants, metrics such as time to exhaustion, heart rate, distance, and calorie expended were collected along with subjective feedback. Statistical analysis showed that both visualization displays significantly improved running performance and satisfaction. Results showed that real-time feedback with data visualization design can positively influence users' understanding and psychological connection to their fitness data. These findings highlight the potential of data visualization to perceive and elevate user experience in exercise interfaces.

1 INTRODUCTION

In today's data-driven era, data visualization plays a crucial role in transforming information into insights, influencing decision-making and behaviors. This is particularly relevant in exercise contexts, where treadmill users often rely on feedback to monitor their performance. However, traditional treadmill displays typically present data in simple text formats. Prior studies have demonstrated the potential of data visualizations to support engagement and behavioral change. Stusak et al. (2014) explored how personalized physical visualizations —such as 3D-printed sculptures of running data could positively affect runners' performance, motivation, and social interactions. Their work showed that physical visualization feedback not only served as passive information but also sparked competition, conversation, and deeper personal engagement, highlighting the importance of meaningful and embodied data representation.

Similarly, Coenen and Vande Moere (2021) examined how situated public visualizations of running statistics on displays in public spaces encouraged social reflection and community dialogue. Their findings emphasized that accessible, interactive visualizations could stimulate casual users to compare, interpret, and discuss their performance with others. Additionally, Kashanj et al. (2024) demonstrated that runners responded more quickly and preferred glanceable visualizations over text when using smartwatches during running, due to the ease of real-time interpretation and enhanced situational awareness.

Building on these insights, this study investigates the transformative potential of well-designed, real-time visualizations embedded within treadmill interfaces to enhance motivation, self-reflection, and exercise performance. While prior research has explored physical, public, and wearable displays that apply to data visualization, a gap remains in understanding the impact of dynamic, on-screen visual feedback during treadmill workouts.

This research aims to bridge that gap through experimental studies. To guide this experimental investigation, we set two research questions:

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1. How does real-time visual presentation of exercise data affect user's running performance?
2. Can improved display with visualization designs lead to increased satisfaction and motivation compared to traditional treadmill displays?

In response to these questions, we apply enhanced real-time data visualization techniques to treadmill exercise interface, focusing on presenting user's activity performance with perceptual clarity, goal motivation, and real-time feedback, which have not been fully explored in previous treadmill visualization studies.

2 RELATED WORKS

This section reviews related works in three areas: exercise performance and feedback indicators, visualization design principles, and the visual feedback in physical activity. These topics provide a foundation for understanding how visualization can support user engagement and satisfaction. A review of these areas also helps identify existing gaps and challenges in designing effective feedback systems. The insights drawn from prior studies inform the development of the visualization strategies proposed in this study.

2.1 Running Performance and User Feedback Indicators

Running performance metrics that are frequently used in previous related studies, Passafiume et al. (2022) examined how visual feedback influences breathing efficiency and time to exhaustion. Schiewe et al. (2020) evaluated smartwatches displaying distance and speed. To assess endurance and performance, time to exhaustion, heart rate, distance covered, and energy expended are frequently used (Nicolò et al., 2019; Walsh et al., 2010). In terms of subjective experience, perceived exertion has been defined as the sense of effort during physical activity by Borg (1982). For clarity and user familiarity, Helms et al. (2016) proposed the revised scale to be a 0-10 scale. User satisfaction is measured via questionnaires, as proven in studies by Cawthon and Moere (2007), Michelle et al. (2013), and Saket et al. (2019), who evaluated visualization effectiveness using both aesthetic and performance-based questions. Yang et al. (2014), Alves et al. (2020), and Carvalho and Chaves (2013) applied user preferences to study how different visualization styles relate to user insights and needs.

These metrics, both objective and subjective, provide a framework for evaluating running performance and user experience, enabling an understanding of how data visualization can influence physical outcomes and motivational responses.

2.2 Visualization Design

To find out how visualization should be designed, Wills Graham (2011) mentioned that line charts and scatterplots are effective options when both variables measure continuous values, especially when one variable is time. Areas may also be used, depending on the quantity being displayed on the y dimension. Myers (1985) suggested that users perceive systems with progress indicators as faster and more satisfying. Harrison et al. (2007) explained how progress bars represent task progress and are usually applied to modern interfaces. Yentes et al. (2012) surveyed that progress bars can improve user enjoyment. This is aligned with the "goal gradient effect" (Hull, 1932), which suggested that effort increases as one approaches a goal. Kivetz et al. (2006) found that this effect also affects consumer behavior. Becker and Pligt (2016) found that people put in more effort toward the end of a goal.

Together, these insights showed that visualization should also be thoughtfully designed to align with human perception and motivation. By leveraging visual elements such as progress indicators or goal-oriented designs, visualizations can enhance user satisfaction and drive toward action.

2.3 Visualization in Physical Activity

Table 1 compares studies that influence physiological performance or user motivation. Ali-Hasan et al. (2006) examined the concept of social data visualization, which helps users to track their fitness data and compare it with other users. Fister was focused on post-session visualization, not real-time feedback. The shift toward real-time visualization for performance enhancement was marked by Crowell et al. (2010), who examined real-time treadmill-based visualization using waveform line chart visual feedback. This approach helped reduce users' impact loading and supported learning and maintaining proper running form technique. The coming of wearable technology expanded real-time feedback beyond treadmills and gym environments. Passafiume et al. (2022) evaluated how real-time animated breathing feedback affected endurance. Unlike

Table 1: Comparative Review of Visualization Techniques in Physical Activity. A check mark (✓) indicates the presence of the corresponding characteristic in each study.

	Moving viewer + Stationary visualization	Display on treadmill	Real-time feedback	Visual activity performance	Data visualization design usage		Evaluate with activity performance	Evaluate with subjective feedback
					Line chart or Bar chart	Progress chart		
Ali-Hasan et al. (2006)				✓	✓			
Nadalutti and Chittaro (2007)				✓	✓		✓	✓
Crowell et al. (2010)	✓	✓	✓		✓			
Stusak et al. (2014)				✓			✓	
Eikey et al. (2015)				✓		✓		✓
Lucas-Cuevas et al. (2018)	✓	✓						
Zhi et al. (2019)			✓		✓			✓
Schiewe et al. (2020)			✓		✓			
Coenen and Vande Moere (2021)	✓		✓	✓				✓
Passafiume et al. (2022)	✓	✓	✓				✓	
Kashanj et al. (2024)			✓	✓	✓	✓		✓
Present study (2025)	✓	✓	✓	✓	✓	✓	✓	✓

distance- or pace-based visualizations, this study showed that breathing synchronization with animation can improve running efficiency, though it did not significantly extend users' time to exhaustion.

While various studies highlight the motivational potential of visualization feedback, their findings are inconsistent, particularly regarding which techniques are most effective across different contexts. However, few have explored how real-time visualizations can be applied to support continuous performance and motivation during treadmill running. To address this gap, this study experimentally investigates the impact of goal-oriented real-time visualizations on users' physical performance and motivation.

3 METHODS

This section outlines the methods used to investigate the impact of visualization during treadmill running. It includes experimental design and the development of the display.

3.1 Experiment Design

Eighteen participants (10 females, 8 males) aged 20 to 26 with prior treadmill experience (minimum 3 hours total usage and regular weekly exercise) were recruited. Each participants attend four treadmill running session over four weeks, with different treatment order to minimize bias. Sessions were spaced approximately one week apart. All participants experienced all conditions.

- T0: Baseline (no display)
- TT: Traditional Display
- T1: Improved Display 1 (line chart and circular progress chart)
- T2: Improved Display 2 (line chart, circular progress chart, and average indicator)

We collected objective and subjective measurement metrics to analyze the difference between treatment in each user.

- Objective measurements: Time to exhaustion, heart rate, distance, calories expended.
- Subjective measurements: Perceived exertion (10-level Borg scale), satisfaction (1-5 scale), use preference.

After each session, participants rated their effort using the 10-level Borg scale and completed a user satisfaction survey. This feedback provided additional insights into their perceptions of the visualization designs.

3.2 Display Design

Line charts were used for speed and heart rate, as related studies supported their use for time-series data (Tufte, 1983; Munzner, 2014). For cumulative data like distance and energy, use half-ring charts to display progress in distance and energy metrics, aligning with the goal-gradient theory (Kivetz et al., 2006). Both Improved display 1 and 2 incorporate a line chart and a half-ring progress chart. Display 2, however, enhances analytical depth by including average heart rate, average speed, and rate indicators for calories and distance

In designing real-time visual feedback for users, we prioritized clarity and minimized cognitive load. We chose a line chart over a bar chart or a scatter plot to represent the trend of speed and heart rate due to its superior performance in communicating continuous data. A line chart allows users to quickly notice and interpret changes over time. Previous studies have shown that line charts outperform bar charts and scatter plots in tasks involving time-series interpretation and correlation detection (Saket et al., 2018). For visualizations that reflect users' progression, we selected a half-ring shape over a bar format. Ohtsubo and Yoshida (2014) found that users perceived faster progress with a circular design, and a half-ring resulted in faster evaluation times compared to a full-ring shape.

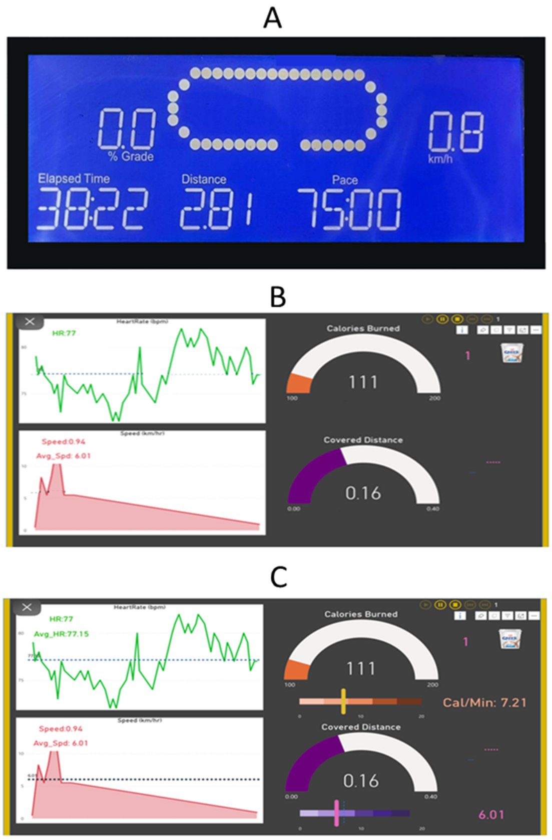

Figure 1: Display format. (A) Traditional treadmill display presents basic metrics such as distance, pace, and speed in text. (B) Improved Display 1 introduces dynamic elements including a line chart of heart rate and a bar chart for speed distribution, along with half-circle progress indicators for calories burned and covered distance. (C) Improved Display 2 builds upon Display 1 by integrating average heart rate, average speed, and additional rate indicators for calories and distance progress.

4 RESULTS

This section presents the experimental results, focusing on two main areas: the analysis of running performance data during the treadmill experiment and the analysis of participant responses from the post-run survey. Collected data were analyzed using both parametric and non-parametric statistical tests to examine potential differences in performance, perceived exertion, satisfaction, and user preference across different display conditions to examine potential differences between treatments.

4.1 Running Performance Analysis

A repeated measure ANOVA was conducted to analyze the differences across treatment groups for the following metrics: duration, distance covered, calories expended, average heart rate, maximum heart rate, average speed, and maximum speed. The analysis identified statistically significant differences among groups for duration, distance covered, and calories expended. To determine the most effective treatment for running performances, a post-hoc Bonferroni test was further performed to compare treatments. The results are as follows:

- Improved Display 2 (T2) and Improved display 1 (T1) have significantly higher duration, and calories expended compared to running without a display (T0) and Traditional Display (TT).
- Improved Display 2 (T2) has significantly higher distance covered compared to running without a display (T0) and Traditional Display (TT).
- No significant difference was found between Improved Display 2 and Improved Display 1.

Table 2: Performance Pairwise Comparison. Statistical significance levels between treatments are indicated as follows: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Metrics	Group1	Group2	t-statistic	Raw p-value	Adjusted p-value
Duration	T0	TT	-1.370	0.188	1.000
	T0	T1	-5.114	0.000	0.000***
	T0	T2	-4.697	0.000	0.001***
	TT	T1	-3.097	0.006	0.039*
	TT	T2	-4.107	0.001	0.004**
	T1	T2	-1.583	0.131	0.790
Distance Covered	T0	TT	-2.296	0.035	0.208
	T0	T1	-3.326	0.004	0.024*
	T0	T2	-4.951	0.000	0.000***
	TT	T1	-1.609	0.126	0.755
	TT	T2	-3.763	0.002	0.009**
	T1	T2	-2.324	0.033	0.196
Calories Expended	T0	TT	-0.956	0.352	1.000
	T0	T1	-3.639	0.002	0.012*
	T0	T2	-4.184	0.001	0.004**
	TT	T1	-3.083	0.007	0.040*
	TT	T2	-4.028	0.001	0.005**
	T1	T2	-1.574	0.134	0.804

4.2 Survey Response Analysis

For perceived exertion level, to find the difference across treatments for exertion levels, we conducted a Friedman test, a non-parametric alternative to repeated measures ANOVA for within-subject design, as the normality assumption was violated in at least one treatment group. We calculated **actual exertion levels** for each participant using their maximum heart rate (Max HR = 220 - Age) and then determined the percentage of maximum heart rate for each participant during treatments. To compare actual exertion with perceived exertion, we mapped each participant's percentage of maximum heart rate to the 10-level Borg scale, where lower values represent lower exertion and higher values indicate near-maximal effort. By comparing actual exertion and perceived exertion values, we analyzed the extent to which treatments influenced users' perception of effort relative to their actual physiological exertion level. A Friedman test revealed no statistically significant difference in exertion levels across treatments ($p = 0.404$). This suggests that no single treatment was significantly more or less demanding than the other in terms of actual and perceived exertion difference. Additionally, we conducted a post-hoc pairwise comparison using the Wilcoxon signed-rank test to further explore potential differences between individual treatments. However, no significant differences were found as well, indicating that Improved Display treatment with real-time data visualization feedback doesn't influence users to experience less perceived exertion level.

To analyze user satisfaction, a Friedman test was performed to evaluate user satisfaction across different treatments for the following metrics: overall satisfaction, clarity of information, relevance of information, aesthetic appeal, ease of use, motivation level, and perceived utility. The analysis result showed that it was significantly different among groups for overall satisfaction, aesthetic appeal, motivation level, and perceived utility.

After that we use Dunn's test to compare between treatment groups:

- Improved Display 2 (T2) has a significantly higher score for overall satisfaction and aesthetic appeal compared to Traditional Display (TT).
- Both Improved Displays scored significantly higher in motivation level and perceived utility compared to Traditional Display (TT).

Table 3: User Satisfaction Pairwise Comparison. Statistical significance levels between treatments are indicated as follows: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Metric	Group1	Group2	p-value
Overall Satisfaction	T2	T1	1.000
	TT	T1	0.107
	TT	T2	0.034*
Aesthetic Appeal	T2	T1	0.893
	TT	T1	0.061
	TT	T2	0.002**
Motivation Level	T2	T1	1.000
	TT	T1	0.014*
	TT	T2	0.003**
Perceived Utility	T2	T1	1.000
	TT	T1	0.005**
	TT	T2	0.001***

After completing the experiment, participants indicated their preferred treatment: 9 preferred Improved Display 2, 6 chose Improved Display 1, and 3 favored the Traditional Display.

5 DISCUSSIONS

This section outlines the discussion of key findings from the experimental results, linking them with prior research and relevant theoretical perspectives. It examines how data visualization influences user performance, perceptions of exertion, and satisfaction. In addition, the discussion highlights the study's limitations and suggests directions for future work.

5.1 Running Performance

The experimental analysis results showed that Improved Display 2 and Improved Display 1 significantly improved running performance for running duration, covered distance, and calories burned compared to running without display and Traditional Displays that provide feedback to users in the form of text. The findings align with several previous studies that highlight the benefits of real-time or physical representations of performance data in enhancing exercise outcomes. For example, both Concon et al. (2024) and Stusak et al. (2014) demonstrated significant improvements in exercise performance. A key similarity between their studies and our study is the use of visualization-based feedback that fosters a sense of achievement and personal progress, which in turn motivates users to exercise with greater effort and consistency. In contrast, the study by Nadalutti & Chittaro, which used the MOPET Analyzer, provided interactive charts and spatial maps to visualize running patterns, but did not offer real-time feedback during exercise.

Likewise, the study by Passafiume et al. (2022), which used only breathing animation without any performance-related visual feedback, did not result in significant performance improvements. One possible explanation is that the breathing animation alone may not be directly related to users' perception of their performance during exercise. Without performance-related cues, users may lack the feedback needed to maintain motivation, making the visual feedback less effective in supporting running performance.

5.2 Perceived Exertion

An observation from the study revealed that Improved Display 1 and Improved Display 2 showed no significant difference from other treatments in reducing perceived exertion, even though their running performance results were significantly better than Traditional Display. This suggests that effort perception level can be influenced by other factors than the way data is represented to users. Marcora et al. (2009) found that perceived exertion does not always correlate with actual physical effort, suggesting that cognitive load of participants can increase perceived exertion independently of physiological effort levels. Stewart et al. (2022) examined the difference between actual exertion and perceived exertion in a VR games exercise experiment. Their findings showed that participants consistently reported lower perceived exertion compared to actual exertion levels. The study suggests that enjoyment of the VR game and the environment (labs and gyms setting) influenced perceived effort, leading users to experience less perceived exertion level. These findings reinforce the idea that perceived exertion is shaped by multiple psychological and contextual factors, such as cognitive load, emotional engagement, and environmental immersion, which helps explain why enhanced visual displays in our study did not reduce perceived effort. It suggests that the user's internal state and environment may play a more significant role in effort perception than the format of data perception.

5.3 User Satisfaction

User satisfaction responses indicate that Improved Display 2 received the highest scores in overall satisfaction and aesthetic appeal. Both Improved Display 1 and Improved Display 2 also scored higher in motivation levels and perceived utility, while the Traditional Display received the lowest scores across all categories. Studies by Zhi et al. (2019) and Kashanj et al. (2024) demonstrated that interactive or real-time visualizations, such as linked layouts or smartwatch gauges, not only improve task performance but also enhance user enjoyment and engagement. Similarly, Coenen and Vande Moere's (2021) study found that situating data visualizations in public spaces fosters emotional and social engagement. These studies, like our Improved Displays, share key characteristics: relevance of data to the user, ease of interpretation under physical or cognitive load, and interactive or dynamic feedback that reinforces self-awareness and motivation. In contrast, a study by Eikey et al. (2015), which manipulated basic visual elements such as the static color of a progress bar chart, found no significant impact on user self-efficacy. The use of color alone lacked meaningful relevance to user progress and did not offer personalization. making it less engaging, especially for long-term goals like 10,000 steps. While our study also used static color, it was applied within a half-ring progress chart and involved a shorter goal (1 km, approximately 1,200 - 1,500 steps). This smaller goal scale may have made progress changes easier to perceive, helping participants feel more motivated to complete the goal.

According to survey feedback, Improved Display 2 was the most preferred, and Traditional Display has the lowest score and is the least preferred. Hildon et al. (2012) review examining found that users often prefer bar charts, despite tables and pictographs being generally better understood. Luera et al. (2024) research shows that users generally prefer visual representations (such as tables and charts) over text-based information due to their efficiency in interpreting trends and comparisons insight. These findings show that users prefer visualization feedback over the Traditional Display that generally represents data in text format.

5.4 Limitations and Future Work

Although the result supports the benefits of real-time data visualization, the study has some limitations that should be addressed in future studies. The sample size of 18 participants may have limited the statistical power of the study. With a larger number of participants, the results might have been more robust and generalizable. However, recruiting participants proved to be challenging due to constraints such as time limitations, specific eligibility requirements, and the intensive nature of the experiment. A smaller sample size increases variability and reduces the generalizability of the study compared to a larger population. Future research should consider using a larger sample to increase confidence in the findings. A future study could examine whether users maintain their exercise engagement and motivation over time with visualization design. The study used a specific type of visualization, but different designs may lead to different results. Future studies should compare different visual elements to determine effective design for boosting performance. The study involved a sample size in a controlled experimental setting, which may not fully generalize to real-world behavior. Future studies may investigate the experiment to test visualization impact in real-world settings, such as gyms or sports grounds.

6 CONCLUSIONS

This study shows the significant impact of real-time data visualization in improving running performance and user satisfaction. In terms of running performance, both Improved Display 1 and Improved Display 2 led to better outcomes in running duration, distance covered, and calories burned compared to the Traditional Display and the control condition. Regarding user satisfaction, Improved Display 2 received the highest ratings in overall satisfaction and aesthetic appeal. In terms of user preference, survey responses confirmed that users favored Improved Display 2, while the Traditional Display was the least preferred. However, perceived exertion did not significantly differ across display types, suggesting that the format of data representation alone may not reduce perceived effort, which could instead be influenced by other cognitive or emotional factors. These insights can inform the design of data and represent interface improvements to foster better user experience and user engagement.

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