Optimal visual fatigue relief method for workers considering rest time allocation

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ABSTRACT Working under the visual display terminal for several hours may cause serious visual fatigue, resulting in production efficiency decrease, and health damage. To address the problem, an optimal break time allocation strategy for workers considering visual fatigue change has been proposed in this paper. First, based on the existing work, a novel visual fatigue change model is established to depict the impact of the continuous work time. On this basis, according to optimization theory, aiming at minimizing the total visual fatigue level, an optimization model is developed to allocate the hourly break time considering the working demand. Additionally, this model is converted as a classic mixed-integer linear programming (MILP) problem and efficiently solved by Gurobi. Finally, a validation experiment with 20 participators is done to verify the effectiveness and superiority of the proposed strategy. The results show that the proposed visual fatigue change model is able to effectively evaluate the actual visual state of workers and predict the visual fatigue development. Additionally, the proposed rest time optimization strategy is able to significantly reduce the visual fatigue level and improve the visual health.

INDEX TERMS: visual fatigue-visual fatigue relief- rest time –optimization method

I. INTRODUCTION
Visual fatigue is an internal manifestation of the decline of human visual ability. It could result in production efficiency decrease, impact comfort, and ruin human health. Generally, rest could effectively reduce the visual fatigue level. Therefore, it is of great significance to reasonably arrange rest time of workers while satisfying the requirements of working hours.

More recently, the visual fatigue problem has aroused the researchers’ concern [1]. For example, [2] has shown that lighting conditions including lighting type, lighting level and related color temperature could affect visual fatigue, and compared with fluorescent lighting, LED lighting inhibits visual fatigue more effectively. [3] has reported that display luminance and ambient illuminance affect subjective comfort evaluation and image quality evaluation, objective visual fatigue index, subjective comfort evaluation and so on. [4] has demonstrated that the lower the blue light ratio (the blue light ratio is 20%, 40%, 60%, 80%, 100%), the deeper the visual fatigue of users. On this basis, numerous indicators are studied to reflect the visual fatigue level. [5] has studied the subjective visual fatigue indicators such as tired eyes, sore or burning eyes, double vision, slowness to focus, blurred vision, dizzy, headache and so on. [6-8] have proved that the significant decrease of the critical flicker frequency (CFF) means the increase of visual fatigue level and the deterioration of retinal function. [9,10] have reported that tear film break-up time (BUT) could be used to evaluate the visual fatigue level. [11] discovered that the near-point accommodation (NPA) would be changed when workers got visual fatigue. [12] has shown that near-point convergence (NPC) would be increased significantly when the visual fatigue was deepened. [13] concluded that the blink duration would increase as the worker got tired. [14] has revealed that significantly shorter blink durations mean a higher workload level. [15] has shown that oxygen saturation (SpO2), and skin temperature (SKT), and galvanic skin response (GSR) were closely related with the visual fatigue or other symptoms. [16,17] have reported that heart rate variability including heart rate, high and low frequency power could effectively reflect the worker’s visual fatigue. Additionally, [18] found that dry eye disease (DED) was associated with significantly lower on-the-job time and significantly affected worker’s productivity using visual display terminals. [19] has investigated the prevalence of ocular surface disease using a written questionnaire and found that the severity of symptoms such as tired eyes and eye discomfort is strongly related to the working time under the visual display terminal. [20] and [21] have demonstrated that with the increasing of working time under visual display terminal (VDT), visual fatigue becomes more serious. [22] has established a visual fatigue evaluation model under LED lights based on long-term visual display terminal work. Focusing on impact factors, numerous indicators, and time dependence trend of visual fatigue, the above literatures have not developed an explicit analytical model to depict the visual fatigue change, which may not provide a direct guidance on fatigue relief.
As a further study, several methods have been used to relieve visual fatigue level. For example, in folk practice, [23] confirmed the clinical efficacy of eye scraping combined with eye point massage in the treatment of visual fatigue. [24] has reported that blink training to increase the blink rate during computer use could relieve dry eye symptoms. In clinical practice, [25] has shown that toric contact lenses, or a spectacle overcorrection could reduce the visual discomfort of individuals with spherical hyperopia and high myopia. [26] noticed that lubricating eye drops and special computer glasses could help improve visual comfort. [27] has demonstrated that acupuncture could significantly improve eye symptoms including visual fatigue, visual acuity, and dry eyes and so on. [28] has proved that the far-infrared rays could accelerate the relief of visual fatigue by expanding capillaries, and improving blood microcirculation. [29] used based-thermal-eye-mask far-infrared (FIR) therapy to reduce the fatigue level and used the fixation frequency (FF) and saccade amplitude (SA) to track the treatment effect. [30, 31] have illustrated the treatment performance of dry eye disease using different colloid drug delivery systems and topical ophthalmic drug delivery systems. However, the result evaluation of the folk practice is relatively subjective, and the effectiveness needs to be further explored. Additionally, the clinical method not only costs a lot of money, but also may increase patients’ pain. Considering the defects, [32] proposed a rest time arrangement method to prevent serious visual fatigue, and demonstrated that a 3 min break each hour could enhance visual performances of individuals. However, the hourly optimal rest time has not been determined, especially considering the requirements of working hours.

With the aforementioned observations, this paper proposed an optimal visual fatigue relief method for workers considering the rest time allocation. First, according to the previous work in [20-22], a visual fatigue change model under visual display terminal was proposed. On this basis, a rest time optimization model integrating working demand constraints was developed to minimize the total visual fatigue level during the workday. By linearizing the nonlinear constraints, a classic mixed-integer linear programming (MILP) problem was obtained and solved efficiently. Finally, a validation experiment with 20 participants was done to verify the superiority of the proposed strategy.

II. PREVIOUS WORK

[22] carried out an experiment on 20 participants’ visual fatigue levels under LED light sources. The levels of visual fatigue were evaluated from three aspects: subjective feeling, ophthalmological parameters, and physiological signals, and the detailed data were measured after 0, 2, 4, 6, and 8 hours of work. By analyzing this data, the visual fatigue prediction model was established.

A. THREE MANIFESTATIONS OF VISUAL FATIGUE

(1) Subjective feeling

Since the subjective feeling of workers was able to directly reflect the visual fatigue level, the questionnaire survey was conducted to evaluate the visual fatigue level. The subjective feeling indicators mainly included tired eyes, sore or aching eyes, irritated eyes, dry eyes, hot or burning eyes, double vision, blurred vision, dizzy and headache. Each indicator was evaluated using a five point system (1=none, 2=slight, 3=moderate, 4=obvious, 5=severe). It was found that the general subjective fatigue state (SS) could be denoted by nine subjective feeling indicator score using a one-component model [22], as follows:

\[ SS(t) = \sum W_i Z_{Si}(t) \]  

where, \( SS(t) \) denotes general subjective fatigue state at hour \( t \), \( Z_{Si}(t) \) was the normalized average relative score of subjective feeling indicator \( i \) at hour \( t \), and \( W_i \) was the weight factor.

(2) Ophthalmological parameters

The ophthalmological parameters including the critical flicker frequency (CFF), the tear film break-up time (TFBUT), best corrected distance visual acuity (BCDVA), best corrected near visual acuity (BCNVA), positive relative accommodation (PRA), negative relative accommodation (NRA), near point accommodation (NPA) and near point convergence (NPC) were related with the visual fatigue level. A one component model was used to depict the relationship between the visual fatigue change and the ophthalmological parameters [22], as follows:

\[ PCop(t) = -0.200 \cdot Z_{NPA}(t) \]
\[ +0.214 \cdot Z_{CFF}(t) + 0.199 \cdot Z_{NRA}(t) \]
\[ +0.216 \cdot Z_{BCDVA}(t) + 0.215 \cdot Z_{BCNVA}(t) \]

where, \( PCop(t) \) stood for the correlation index of visual fatigue, \( Z_{NPA}(t) \), \( Z_{CFF}(t) \), \( Z_{NRA}(t) \), \( Z_{BCDVA}(t) \), and \( Z_{BCNVA}(t) \) represented the normalized average relative NPA, CFF, NRA, BCDVA, and BCNVA values, respectively.

(3) Physiological signals

The physiological signals including skin temperature (SKT), galvanic skin response (GSR), and eye blink could reflect the visual fatigue level [22], as follows:

\[ PCps(t) = -0.376 \cdot Z_{SKT}(t) \]
\[ +0.376 \cdot Z_{GSR}(t) + 0.347 \cdot Z_{Eyeblink}(t) \]

where, \( PCps(t) \) expresses the correlation index of visual fatigue, \( Z_{SKT}(t) \), \( Z_{GSR}(t) \), and \( Z_{Eyeblink}(t) \) are the normalized average relative SKT, GSR and eye blink values, respectively.

B. VISUAL FATIGUE PREDICTON MODEL

Through data analysis, it was found that the level of visual fatigue could be inferred according to \( PCop(t) \) and \( PCps(t) \). The prediction model was expressed as follows [22]:

\[ ESS(t) = -0.588 \cdot PCop(t) + 0.426 \cdot PCps(t) \]
\[ ESS(t) \approx SS(t) \]

where \( ESS(t) \) means the inferred visual fatigue level.

The existing work shows that the visual fatigue could be acquired by measuring ophthalmological parameters and physiological signals, which lays a technical foundation for the evaluation of visual fatigue.
III. PROBLEM FORMULATION

According to company regulations and employment law, workers are allowed to take a rest during the shift. To significantly relieve the visual fatigue, a visual fatigue change model and a rest time optimization model were developed in this paper.

A. VISUAL FATIGUE CHANGE MODEL

![Figure 1: Relationship between the subjective level of visual fatigue and working time.](image)

The black solid line in Figure 1 depicts the relationship between the visual fatigue level and working time in [22]. As observed from the figure, with the increasing of the working time, the visual fatigue level would rise simultaneously. However, the change rate of the visual fatigue is not monotonous on the time scale. For example, the visual fatigue level would increase by 1.25 scores from 0 to 2 hours, 0.4531 score from 2 to 4 hours, and 0.6719 score from 4 to 6 hours. To directly depict the change trend of the curve, a visual fatigue mathematical model was established in this paper, as follows:

\[
SS(t) = \begin{cases} 
  k_{10} + k_{11} \times L(t), & \text{if } 0 \leq L(t) \leq 2 \text{ is satisfied} \\
  k_{20} + k_{21} \times L(t), & \text{if } 2 < L(t) \leq 4 \text{ is satisfied} \\
  k_{30} + k_{31} \times L(t), & \text{if } 4 < L(t) \leq 6 \text{ is satisfied} \\
  k_{40} + k_{41} \times L(t), & \text{if } 6 < L(t) \leq 8 \text{ is satisfied}
\end{cases}
\]

(6)

where \( k_{10}, k_{11}, k_{20}, k_{21}, k_{30}, k_{31}, k_{40}, \text{ and } k_{41} \) are equation parameters, \( L(t) \) represents the continuous working time of the worker at hour \( t \). For example, when a worker works at hour 1 and hour 2, rests at hour 3, and then works again at hour 4, \( L(t) \) could be represented as \( L(1) = 1, L(2) = 2, L(3) = 0, L(4) = 1 \).

On this basis, to facilitate analysis, the existing visual fatigue curve was moved upward to ensure all the possible fatigue levels were not less than 0, as depicted by the red dotted line in Figure 1. Therefore, a visual fatigue change model was established in this paper, as follows:

\[
SS^*(t) = SS(t) + k_0
\]

(7)

where \( SS^*(t) \) denotes the novel general subjective fatigue state of the worker at hour \( t \), \( SS^*(0) = 0 \) is satisfied, and \( k_0 \) is a positive number.

Based on the visual fatigue change model, a rest time optimization method was proposed, as illustrated in details in following section.

B. OPTIMIZATION MODEL

Optimization theory is a theoretical method about the optimal design, optimal control and optimal management of systems [33]. It aims to maximize or minimize the objective function of the system while meeting the system operational constraints. This method has been used widely in energy management of power grid [34], operation control of machines [35], logistics distribution [36] and so on. Considering the working time constraint, optimization theory would be used in this paper to allocate the hourly rest time, in order to relieve the visual fatigue, as follows:

A lower level of visual fatigue means higher productivity and better health states. Therefore, the objective function was set to minimize the cumulative sum of fatigue level of the workers during the workday, as follows:

\[
\min \sum_{t=1}^{T} SS^*(t)
\]

(8)

where \( T \) stands for the length of working hours.

Also, the workers must satisfy working requirements such as working time. The detailed constraints were presented as follows:

1) Hourly rest time constraint
The rest time of workers at hour \( t \) shall be less than one hour. The corresponding constraint was denoted as follows:

\[
U(t) \tau \leq R(t) \leq U(t)
\]

(9)

where, \( R(t) \) stands for the rest duration within hour \( t \), \( \tau \) means the minimum rest time, the binary variable \( U(t) \) marks the rest behavior, where \( U(t)=1 \) means workers take a rest at hour \( t \), and \( U(t)=0 \) indicates workers do not rest at hour \( t \).

2) Rest frequency constraint
According to company regulations, the rest frequency shall not be more than the allowable value:

\[
\sum_{t=1}^{T} U(t) \leq N1
\]

(10)

where \( N1 \) expresses the number of the allowed frequency.

3) Total rest time constraint
The total rest period for workers could not exceed the number of hours allowed during the workday, as follows:

\[
\sum_{t=1}^{T} R(t) \leq N2
\]

(11)

where \( N2 \) represents the allowed total rest time during the workday.

4) Associative constraint

\[
\sum_{t=1}^{T} L(t) \leq 8
\]

(12)

where the \( L(t) \) represents the continuous working time of the workers at hour \( t \).
There was an associational constraint between the rest time and continuous working time, as follows:

\[ L(t) = \begin{cases} 1 - R(t), & \text{if } R(t) > 0 \text{ is satisfied} \\ L(t - 1) + 1, & \text{if } R(t) = 0 \text{ is satisfied} \end{cases} \tag{12} \]

Note that \( R(t) > 0 \) means that the worker takes a rest within hour \( t \), and \( R(t) = 0 \) indicates that the worker does not rest at time \( t \). Therefore, when \( R(t) = 0 \) is satisfied, the continuous working time at hour \( t \) is related with the continuous working time at hour \( t - 1 \).

IV. SOLUTION ALGORITHM

A. MODEL SOLUTION

The optimization problem included nonlinear constraints (i.e., (6) and (12)), which made it difficult to be solved. To address the problem, the optimization model was first linearized as a classic mixed-integer linear programming (MILP) problem, and solved by heuristic solvers [34]. The detailed descriptions were presented as follows:

With regard to (6), first, define that binary variables \( U_i(t) \) \((i=1,2,3,4)\) denote four possible working time scenarios. For example, \( U_1(t) = 1 \) denotes that the continuous working time is satisfied by \( 0 \leq L(t) \leq 2 \), and \( U_1(t) = 0 \) represents the continuous working time is satisfied by \( L(t) > 2 \). Considering that the worker has only one general subjective fatigue state at any hour \( t \), the constraint could be denoted as follows:

\[
L(t = 1) + U_2(t) + U_3(t) + U_4(t) = 1
\tag{13}
\]

On this basis, (6) was represented as follows:

\[
SS(t) = \left[k_{10}U_1(t) + k_{11}L_i^* (t)\right] + \left[k_{20}U_2(t) + k_{21}L_i^* (t)\right] + \left[k_{30}U_3(t) + k_{31}L_i^* (t)\right] + \left[k_{40}U_4(t) + k_{41}L_i^* (t)\right] 
\tag{14}
\]

where, the variable \( L_i^* (t) \) \((i=1,2,3,4)\) stands for \( L(t) \times U_i(t) \), and it could be linearized as follows:

\[
0 \leq L_i^* (t) \leq L(t)
\tag{15}
\]

\[
-J + U_j(t) \times J + L(t) \leq L_i^* (t) \leq U_j(t) \times J
\tag{16}
\]

where, \( J \) means a large positive number.

With regard to (12), first, define that continuous variables \( R^* (t) \) and \( L^* (t - 1) \) represent \( R(t) \times U(t) \) and \( L(t - 1) \times U(t) \), respectively. The linearization equations could be expressed as follows:

\[
0 \leq R^* (t) \leq U(t) \times J
\tag{17}
\]

\[
-J + U(t) \times J + R(t) \leq R^* (t) \leq R(t)
\tag{18}
\]

\[
0 \leq L^* (t - 1) \leq U(t) \times J
\tag{19}
\]

\[
-J + U(t) \times J + L(t - 1) \leq L^* (t - 1) \leq L(t - 1)
\tag{20}
\]

On this basis, (12) could be replaced by the following formulas:

\[
L(t) = 1 + L(t - 1) - R^* (t) - L^* (t - 1)
\tag{21}
\]

where \( \varepsilon \) is a very small positive number.

Through the above process, the optimization model was converted as a classic MILP problem, as follows:

\[
\min \text{Ex} \tag{22}
\]

s.t. \( Ax = C \tag{23} \)

\( Bx \leq D \tag{24} \)

where \( X \) means the variable matrix in the optimization model, \( \mathbf{A}, \mathbf{B}, \mathbf{C}, \) and \( \mathbf{D} \) stand for the coefficient matrices. (22) represents (7), (23) stands for (7), (13), (14), and (21), and (24) means (8)–(11), and (15)–(20).

Based on a 4.3-GHz Windows-based PC with 16 GB of RAM, the optimization problem was coded in MATLAB and solved using Gurobi called by Yalmip.

B. STATISTICAL ANALYSES

We used SPSS V.25.0 (IBM Corp) to analyze the data. We calculated the average and SD of the variables and used t-test to evaluate the characteristics. Define the threshold for statistical significance as 0.05.

V. RESULTS

A. EXPERIMENT CONDITIONS

To verify the superiority of the proposed method, 20 individuals participated in the experiment. All of them came from Bengbu Medical College and satisfied the criteria in Table I. Additionally, their eyesight was corrected to reach the best visual acuity.

**TABLE I. THE INCLUSION CRITERIA**

| Item | Inclusion criteria |
|------|--------------------|
| Age  | 20-30 years        |
| Best visual acuity | ≥1.0 for both monocular and binocular |
| Myopic refractive error | ≤6 dioptres for both monocular |
| Anisometropia | ≤1 dioptre |
| Tear break-up time | ≥10 seconds |
| Astigmatism | ≤-1 dioptre |
| Severe cardiovascular and cerebrovascular diseases | No |
| Colour blindness | No |
| Colour feebleness | No |
| Severe dry eye | No |
| Amblyopia | No |
| Heterophoria | No |

Without loss of generality, the experiment time was from 9:00 to 17:00. The allowed rest time and frequency were 1.5 hours and 2 times, respectively. To evaluate the effect of proposed method, all the participants took part in the following two experiments on different days:

Case 1: The participants followed the optimization result to take a break.

Case 2: Without loss of generality, the participants took a break at 12:00-12:45 and 15:00-15:45.
According to [22], the ophthalmological parameters and physiological signals of all the participators were measured to obtain the level of visual fatigue.

B. RESULT ANALYSIS

Table II shows the optimal rest time in theory in case 1. As observed from the table, workers shall rest for 30 min at 11:00-12:00 and 60 min at 14:00-15:00. In this case, the total level of visual fatigue of workers during the workday would be 5.6873. For comparison, according to the mathematical model in (7), the total level of visual fatigue in case 2 would be increased to 6.0095. The theoretical results show that the proposed strategy could significantly relieve the visual fatigue.

| Time       | Rest time |
|------------|-----------|
| 9:00-10:00 | 0         |
| 10:00-11:00| 0         |
| 11:00-12:00| 30 min    |
| 12:00-13:00| 0         |
| 13:00-14:00| 0         |
| 14:00-15:00| 60 min    |
| 15:00-16:00| 0         |
| 16:00-17:00| 0         |

All the participators carried out the rest decisions in case 1 and case 2 on different days. The actual values of total visual fatigue states of participators during the workday are illustrated in Table III. As observed from the table, the actual values of the visual fatigue level in case 1 and case 2 were 5.6870±0.1098 and 6.0085±0.2683, respectively. Some laws have been found as follows:

1) According to the theoretical value and actual value in case 1, \( p=0.990 \) was obtained using t-test. Meanwhile, \( p=0.987 \) was obtained using t-test by analyzing theoretical value and actual average value in case 2. Therefore, there was a significant interaction between the theoretical and actual value.

2) By analyzing the actual values in case 1 and 2, \( p=0.01 \) was obtained using t-test. Therefore, there was a significant difference between the actual values in case 1 and case 2.

| Total Visual Fatigue States of Participators During the Workday |
|---------------------------------------------------------------|
| Theoretical value   | Actual value (\( \bar{x} + s \)) |
|---------------------|----------------------------------|
| Case 1              | 5.6873                           |
| Case 2              | 6.0095                           |
|                     | 5.6870±0.1098                    |
|                     | 6.0085±0.2683                    |

C. IMPACT OF REST DURATION AND WORK TIME REQUIREMENTS

The rest duration and working time requirements may impact the visual fatigue state of the workers. To verify the advantages of the proposed strategy in various conditions, the corresponding experiments were carried out.

Assuming that the working time is 8 hours, Figure 2 shows the impact of break duration on the visual fatigue state. As observed from the figure, with the increase of rest time, the level of visual fatigue was reduced simultaneously, indicating that the longer the rest time, the better the visual health. Additionally, compared with that in case 2, the level of visual fatigue in case 1 was always lower.

Assuming that the break duration is 1.5 hours, Figure 3 depicts the impact of working time on the visual fatigue state. As observed from the figure, with the increase of working time, the level of visual fatigue gradually deepened, implying that the shorter the working time, the better the visual health. Additionally, unlike that in case 2, the visual fatigue in case 1 was more slight.

D. DISCUSSION

Benefiting from the convenience, nowadays the visual display terminal has been widely in offices. Meanwhile, Then, the problem of visual fatigue also occurs frequently, which not only reduces the productivity and comfort, but also endangers the health of workers. Therefore, it is necessary to relieve visual fatigue.

Previous studies have shown that the visual fatigue was related to the working time and the severity of symptoms depended on the length of work hours [19-22]. However, the analytical relationship between the level of visual fatigue and working time has not been given.

In our study, a visual fatigue change model based on the analytical method was established. By inputting the continuous
working time into this model, the theoretical levels of visual fatigue of 20 participants could be calculated, and there was no significant difference between the actual and theoretical values \( p=0.990 \) in the rest-time optimization group and \( p=0.987 \) in the routine group. On the one hand, our study demonstrated that the level of visual fatigue was positively correlated with working hours. On the other hand, the results showed that the actual level and development trend of visual fatigue could be accurately evaluated and predicted using the proposed visual fatigue change model.

Previous studies noted that eye scraping combined with eye point massage and blink training to increase the blink rate were helpful in the treatment of visual fatigue [23, 24]. In addition, toric contact lenses, a spectacle overcorrection, lubricating eye drops and special computer glasses, acupuncture, far-infrared rays, colloidal drug delivery systems and topical ophthalmic drug delivery systems were able to relieve symptoms of visual fatigue [25, 31]. However, these methods may not be able to balance the treatment effect, treatment cost, and comfort. Although a 3 min break each hour could improve visual performances, the working requirements in real scenes did not be considered [32].

In our study, a visual fatigue relief model for workers was developed considering working hour constraints, where optimization theory and linearization techniques were used to guide the rest time allocation. By inputting working requirements into this model, optimal rest time decisions were obtained. 20 participators were invited to take part in a validation experiment. The results showed that there was an obvious difference in visual fatigue levels before and after optimizing the rest time \( (p=0.01) \). Therefore, the proposed rest time optimization model was able to effectively relieve the visual fatigue.

Previous studies have shown that the lighting conditions including lighting type, lighting level and related color temperature, display luminance, ambient illumination, blue light ratio and so on could impact the visual fatigue [2-4]. However, once the office was decorated, these factors may hardly be changed.

In our study, the impact of company management regulations such as allowed rest duration and work time requirements was analyzed. The results showed that a longer rest time and shorter working time meant a lower visual fatigue level of workers. Additionally, by inputting different time management regulation into the proposed optimization model, an optimal hourly rest time decision could be obtained. The results showed that following the optimal rest time decision could always obtain a lower level of visual fatigue. Therefore, the proposed strategy could always effectively relieve the visual fatigue under different rest duration and working time.

VI. CONCLUSIONS

This paper mainly studied the visual fatigue relief method for workers considering the rest time allocation. The proposed visual fatigue change model could provide accurate and useful information to infer the visual fatigue state and predict the visual fatigue development of workers. The proposed optimization model is able to significantly relieve the visual fatigue by reasonably allocating the rest time while satisfying the work requirement. This method could be used in different companies to improve productivity and employee health.

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Conflict of interest All authors declare that they have no potential conflicts of interest in the research, authorship, and publication of this article.

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