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Evaluation of Cognitive Load Differences between Elderly and Young Pedestrians at the Signalised Intersection

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ABSTRACT

The pedestrian cognitive load has an important effect on the pedestrian crossing decision making. Compared with young adults, old people are characterised by declining physical function and slower reaction ability, which makes them prone to traffic accidents when crossing the street. This study aims to compare the visual information-mental load correlation between elderly and young adults waiting at the signalised intersections and evaluate their cognitive load conditions. Therefore, two signalised intersections with different traffic scenes in the Nan'an District, Chongqing, China were selected. The eye-tracking, electrocardiographic and electrodermal activity data of young and old pedestrians were collected using eye-tracking and physiological instruments. The visual indexes (the total duration of fixations, the number of fixations, the average pupil diameter changing rate, the number of saccades, the average peak speed of saccades, the average amplitude of saccades and the total amplitude of saccades) and physiological indicators (the average growth rate of heart rate, the time-domain analysis indicator of HRV and HRV frequency domain analysis indicators, electrodermal response amplitude and rise time of the EDR amp.) were taken as inputs and outputs parameters, respectively. Then, the comprehensive cognitive load evaluation model for pedestrians was constructed when waiting to cross the street based on the data envelopment analysis method. And the cognitive load characteristic differences between the young adults and the elderly were compared. The results show that in the same crossing scene, compared with the young pedestrian, the elder pedestrian exhibited lower overall perceptual efficiency, lower fixation durations and higher cognitive loads. These results can provide certain references on improving the street crossing safety for the elderly pedestrian.

KEYWORDS

traffic safety; pedestrian crossing; cognitive load; data envelopment analysis; eye tracking experiment; physiological experiment.

1. INTRODUCTION

Data from the Chinese Traffic Management Research Institute of the Ministry of Public Security show that the number of elderly people killed in traffic accidents has been annually increasing, with an annual average increase of 9% [1]. Compared with other groups of pedestrians, elderly pedestrians have a lower walking speed and longer crossing time in signalised intersections [2]. Currently, the signalised intersection facility setting and designing have not fully considered the crossing characteristics of elderly pedestrians. Due to the deterioration of their bodily functions, the elderly people's reflexes, judgment and concentration are not as good as those of the young people, so the crossing time would not be enough, and sometimes it is even necessary to cross the street using twice the green display time. As a result, elderly pedestrians usually feel nervous and impatient when crossing at signalised intersections. This is more likely to cause them to make wrong decisions and behaviour, affecting personal safety [3].

In the aspects of studies related to pedestrian crossing, Lan et al. [4] found that pedestrian-vehicle conflicts during the evening rush hour were more frequent in intersections without dedicated right-turn phases. Jain et al. [5] found that characteristics such as gender and age can affect the average crossing speed of pedestrians. Biassoni et al. [6] found that adults were more inclined to have a saccade of their surroundings for useful information and spend longer time observing different areas in their field of vision when crossing the street. Tapiro et al. [7, 8] investigated the effects of roadway environment and age on the pedestrians' visual attention.

For the old people, the decline in physiological functions of the elderly leads to a decline in their attention span and makes it difficult for them to react and make timely judgments in the face of danger. Zeeger et al [9] found that older people are slower to respond to external stimuli and are more likely to be nervous when faced with more complex crossing scenarios; Dommes et al [10] found that traffic flow conditions are the biggest risk factor for the safety of street crossing among the elderly people, and that due to the decline in judgment and the distraction of attention, the elderly pedestrians are more inclined to make aggressive street crossing strategies; Oxley et al.'s [11] experimental study showed that older people's cognitive ability to perceive the distance and speed of vehicles was significantly lower than that of the young adults, which also led to a greater tendency to make aggressive crossing decisions; In addition, Dommes et al. [12] concluded that older adults make slower crossing decisions, act slower and have a reduced ability to judge safe gaps, all of which makes them more at risk when crossing streets.

Cognitive load refers to the total amount of mental activity exerted on an individual's cognitive system during a specific operating time [13]. In terms of studies related to cognitive load with eye movement and physiological indicators as the main parameters, Lee [14] investigated the interactions of endogenous and exogenous factors with cognitive load and found that endogenous factors can significantly affect saccade modes, and complex scenes can reduce gaze time. Mikula et al. [15] found that the combination of eye and head movements can provide relevant information about the cognitive demands of a subject's perception of a complex task. Ahn et al. [16] collected electroencephalogram (EEG) and heart rate variability (HRV) data from subjects and used a support vector machine classifier to differentiate between their task and resting baseline states. Barua et al. [17] collected EEG, electrooculogram (EOG), electrocardiogram (ECG) and electromyography (EMG) data from 66 subjects and investigated the correlation between cognitive load and driving performance. Bailey et al. [18] evaluated the workload of the subjects using the average percentage change in pupil diameter as a typical parameter. Liu [19] quantified the cognitive load level. Liu [20] investigated selective attention and concluded that the attention-driving mechanism determined the allocation of attention in a search task. Liang et al. [21] found that pedestrians directed more of their gazes to approaching vehicles and that pedestrians spent significantly more time looking at the approaching vehicles that were closer. Lanzer et al. [22] investigated the gaze and behavioural gestures of pedestrians when crossing a street. They found that pedestrians with street crossing instructions were somewhat affected in their gaze behaviour, while their behavioural postures while crossing the street were not significantly affected.

For visual information extraction, some scholars have used pictures as experimental stimuli to study the observation and perception of pedestrians. For example, Bianchi et al. [23] designed three experimental scenarios involving real-life situations and video simulation to explore the effect of cognitive load on attention. They found that the effect of cognitive load on attention in the video simulation was similar to that in the real-life situation. Zhu [24] took three sets of photographs of intersections to explore the correlation between gender and risk perception and concluded that men showed better early visual processing of traffic scenes. Biassoni [6] used an eye-tracking device to collect eye movement indicators of subjects while observing four pictures of a crossing scene. The fixation was used as the main indicator to study the visual search strategy of these subjects while observing the pictures. It was found that children showed lower abilities in visual search for traffic environments and risk recognition and were more difficult to engage in safe crossing behaviour.

Overall, the cognitive load of pedestrians has been studied to some extent worldwide. However, the number of indicators adopted for evaluation is limited, failing to comprehensively respond to the cognitive load of pedestrians when crossing the street from multiple perspectives. The safety of crossing at signalised intersections is a serious problem for the elderly, and the cognitive load can affect the crossing decision making for the elderly pedestrian. Now, the elderly pedestrian cognitive load is ignored when designing and setting the traffic facility, so it has important meaning comparing the difference in cognitive load between the elderly and the young pedestrians at signalised intersections. In this paper, typical eye movement and physiological indicators were selected to characterise the cognitive load of pedestrians crossing streets. Then, we analysed the cognitive load differences between elderly and young pedestrians in different scenes and the potential traffic environment contributing factors to the differences. This study can provide some references when design and set the transportation infrastructure, then the elderly people's cognitive load can be deduced when waiting to cross the signalised intersection and make the proper crossing decision, thus the old people's street-crossing safety can be improved.

2. METHODOLOGY

2.1 Experimental setup

Pedestrians who engage the behaviours associated with generalising, organising and other processing information in the crossing scenarios, generate cognitive load and excessive cognitive load will reduce the efficiency of information interaction and cause tension in pedestrians [25]. Since the biological evaluation method of biological indicators has a greater advantage in objectivity and reliability [26], this paper utilises the biological evaluation method to study the cognitive load of pedestrians when crossing the street by collecting their eye movement parameters and physiological indicators [27].

Experimental method

Based on the following considerations, the indoors experiment was finally selected to complete the data collection.

1) The indoor simulation experiment can effectively control the experimental environment, exclude the uncertainty factors in the real scene, and improve the controllability and safety of the experiment; at the same time, it can ensure that each subject receives the same information about the external traffic environment, and will not lead to different results of the collected data due to different traffic environments.
2) Since the elderly recruited for the experiment are all over 60 years old, their physical fitness is generally poor. When conducting the pre-experiment, the elderly generally reflected a strong sense of pressure and dizziness after wearing the eye-tracking device while standing, and a stronger sense of discomfort after wearing it for a long period of time, which may have a greater impact on the experimental data, so the final decision was made to use the picture as a stimulus to allow the elderly to carry out the simulation experiment indoors in a seated position.
3) Considering the aspect of the influence of the indoor simulation experiment on the experimental results, some scholars have used pictures as experimental stimulus materials to study the observation and perception of pedestrians.

The above study suggests that it is feasible to conduct simulation experiments using pictures as experimental materials in exploring visual search and early perception of pedestrians. Although the use of pictures as experimental stimulus materials has some limitations and cannot simulate the sound and other information of the surrounding environment when pedestrians are waiting to cross the street, it can present most of the key information needed when pedestrians are waiting to cross the street. Since street crossing behaviour has not been studied, pictures can be used as experimental stimulus materials to analyse the visual search characteristics of pedestrians waiting to cross the street, and then explore the external factors that cause the older adults to have a greater mental load. Therefore, the indoors traffic videos were used as experimental materials in order to investigate the visual search and early perception of pedestrians.

This paper aims to investigate the differences in the attention to the influencing factors in the traffic environment between elderly and young pedestrians when crossing the street. Elderly and young volunteers were recruited to complete the experiment. This experiment involved many recruits. The study was limited to the process of waiting to cross the street after the crossing location was selected and did not involve the process of crossing the street after the green traffic light. Considering the experimental safety of the elderly subjects, the experiment was conducted indoors for data collection: watching the video of the crossing scene indoors to conduct a simulation experiment and collecting eye movement and physiological indicators of the subjects by using the Tobii Pro Glasses 2 eye-tracker and PhysioLab wireless physiograph (*Figure 1*).

a) Instrument wearing photo *b) Display device showcase*

Figure 1 – Experimental method

Experimental volunteer

A total of 112 experimental volunteers (60 men and 52 women) were recruited, including 45 young volunteers and 67 elderly volunteers. The young volunteers were mostly undergraduate and graduate students, and the experimental data collection for the older volunteers were conducted in-depth in neighbourhoods with a high number of elderly people. The volunteers could choose a gift after finishing the experiment. All the young volunteers were aged 20~30 years old, and the elderly volunteers were aged 60 and above. The age and gender distributions of the volunteers are shown in *Table 1*.

Table 1 – Age and gender distribution of the volunteers

Gender	Age distribution and number of participants [person]				
	20~30 years old	60~69 years old	70~79 years old	80 years old and over	Total
Male	18	29	7	6	60
Female	27	16	6	3	52
Total	45	45	13	9	112

Experimental design and procedure

It has been shown that two external environmental factors (types of safety island and curbstone steps) have a greater impact on the street crossing of elderly pedestrians [27 – 29]. Based on the field investigation, two traffic scene videos of pedestrians waiting to cross the street at the red light at the Huilong Road-Lanhua Road intersection in the Nanan District of Chongqing Municipality, China were finally selected as the experimental stimuli. Scene video A was from the east entrance in the direction of south to north and Scene video B was from the west entrance in the direction of south to north. The traffic data of the entrance are listed in *Table 2*.

Table 2 – Statistical description of traffic data

The crosswalk number	Number of lanes [lane]	Pedestrian crossing length [m]	Curb ramp setting	Buffer facilities	Safety island	Pedestrian signal cycle [s]	Pedestrian green time [s]
A	5	27	0	0	0	115	32
B	8	30	1	1	1	115	25

Note: In the three traffic parameters Curb ramp setting, Buffer facilities and Safety island, 1 means yes or have, 0 means no or none.

The countdown numbers on the signal panel were visible on the display screen. The videos were captured in off-peak hours during the daytime when the weather was clear, and traffic and pedestrian flows were lower. The curbstone steps at the pedestrian crosswalk in Scene video A *Figure 2a* did not contain a gentle slope, and there was no safety island for secondary pedestrian crossing. The pedestrian crosswalk in Scene video B had a gentle slope and a safety island *Figure 2b*.

a) Screenshot from Scene Video A b) Screenshot from Scene Video B

Figure 2 – Pedestrian crossing scene

Before the experiment, the researchers assisted the volunteers in wearing the PhysioLAB wireless physiograph to ensure that no noise occurred during the physiological data collection. Then, the volunteers were required to wear the eye-tracking device connected to the computer and calibrated with their visions through a calibration card. During the experiment, the volunteers watched two scene videos of waiting to cross the street shown on the display device successively to simulate the visual search scenarios and physiological responses of pedestrians waiting to cross the street at signalised intersections. All experimental participants watched two separate identical videos. Participants did not necessarily start crossing the street as soon as the green light came on; when the participant decides to cross the intersection, they can give a signal to the recorder to record this information, i.e. they can stop the video with the remote controller. Simultaneously, the researchers stopped recording data and the experiment was finished. At the end of the experiment, the eye movement and physiological data were temporally synchronised and organised through video playback.

The experiment measured seven oculomotor metrics: total gaze point duration, number of gaze points, mean pupil diameter rate of change, number of sweeps, mean peak velocity of sweeps, mean amplitude of sweeps and total amplitude of sweeps; as well as seven physiological metrics: mean heart rate growth rate, heart rate variability (HRV) time domain analysis metrics of the standard deviation of the R-R interval (SDNN), HRV frequency domain analysis metrics LF, HRV frequency domain analysis metrics HF, HRV frequency domain analysis metrics LF/HF, peak electrocorticographic response (EDR amp.), and peak electrocorticographic arrival time (EDR rit.).

Data processing

After the experiment was completed, the eye movement and physiological data were processed by using the Tobii Pro Lab and PhysioLAB software, respectively. There are 112 experimental volunteers' data. The valid sampling rate for each participant means to correctly identify the proportion of the number of samples taken to the eyeball to the total number of samples. Each volunteer' data with a valid sampling rate of 85% or more [28] have high research value, so samples with a valid sampling rate of less than 85% need to be removed. During the experiment, if the collected data was abnormal due to the subject's personal reasons, such as the physiological instrument patch falling off or the volunteer's strenuous excise, such data were to be eliminated. Missing data due to the unstable connection between the physiological instrument and the computer equipment, the lack of ECG or electrodermal data, i.e. incomplete data of various indicators of the same subject, were also directly excluded. Finally, the experimental data of 30 elderly pedestrians and 30 young pedestrians were included in the analyses.

2.2 Evaluation methods

Identification of evaluation indicators

1) *Eye movement indicators.* Pedestrians acquire traffic information through visual search while crossing the street. Fixation and saccade are the main eye movement forms of pedestrians to acquire information about the environment. Fixation is a form of eye movement for pedestrians to extract a certain feature in the traffic environment, with a certain duration and gaze position. Referencing the existing studies, considering the present experimental program and the basic data conditions, this paper took the following eye movement indexes as the typical characterisation parameters reflecting the cognitive load of pedestrians: the total dura-

tion of fixations, the number of fixations, the average pupil diameter changing rate, the number of saccades, the average peak speed of saccades, the average amplitude of saccades and the total amplitude of saccades.

2) *Physiological indicators.* Relevant studies have shown that it is feasible and effective to use physiological parameters to assess psychological stress [29]. Physiological indicators, such as ECG, EDA and EOG, contain a large amount of information related to psychological stress. Reasonable using of these indicators can facilitate a more objective evaluation of the subject's psychology and stress. This experiment collected the ECG and EDA data of the subjects using the PhysioLAB wireless physiometer. Then, the physiological indicators were extracted and processed by the software. After that, the ECG indicators were selected, including the average growth rate of heart rate, the time-domain analysis indicator of the HRV (i.e. the standard deviation of normal-to-normal R-R intervals (SDNN)) and HRV frequency domain analysis indicators (i.e. LF, HF and LF/HF). HF refers to the high frequency, which generally responds to information about parasympathetic activation; LF refers to the low frequency, which generally responds to information about sympathetic activation; LF/HF refers to the low frequency to HF energy ratio, which responds to balanced autonomic control. The EDA indicators included the electrodermal response amplitude (EDR amp.) and rise time of EDR amp. (EDR rit.). These indicators were included in the evaluation model.

Model analysis

Data envelopment analysis (DEA) is widely used in operations research and economics. DEA has a unique advantage in dealing with systems with multiple inputs and outputs indicators and can evaluate the relative effectiveness among decision making units (DMUs) [30]. The DEA method has strong applicability for the pedestrian cognitive load evaluation, which is mainly reflected in the following aspects. *Equation 1* The visual search and physiological response when waiting for pedestrians crossing the street has a complex influence mechanism on the cognitive process and decision-making behaviour of pedestrians, and the characterisation indexes include the pedestrian's eye-movement indexes and physiological and psychological indexes, and the process of comprehensively evaluating this special cognitive load system through multiple inputs and multiple outputs just happens to have a certain degree of similarity and mutual adaptability with the principle and method of the DEA. *Equation 2* The visual search and physiological reaction of pedestrians waiting to cross the street in the comprehensive evaluation process of the pedestrians' cognitive process and decision-making behaviour, the inputs and outputs are constructed with different types of index data, and the complex relationship between the inputs and outputs is difficult to be expressed in quantitative terms, while the DEA planning and calculation process permit a solution without determining the premise of such a relationship, and this feature provides a comprehensive evaluation of the cognitive load. This feature provides favourable conditions for the comprehensive evaluation of cognitive load. *Equation 3* The comprehensive evaluation index system of cognitive load includes the eye movement and physiological and psychological parameters of pedestrians, whose unit scale is inconsistent, while the DEA can ignore the step of normalising the data.

The DEA method generally shows "efficient" and "inefficient" to indicate whether the resource inputs of each DMU in the input-oriented DEA model have reached the optimal allocation. "Effective" means that the amount of input resources is relatively minimal with constant output, and the DEA efficiency value reaches 1, i.e. the best practice frontier is reached. The calculation method of the model is as follows. Let there be n decision-making units, and each decision-making unit has m input indicators and s output indicators. Thus, the CCR model for evaluating the effectiveness of the j_0^{th} decision unit is expressed as

$$f(\theta)\min[\theta - \varepsilon(e_m^T S^- + e_m^T S^+)] \tag{1}$$

$$\left.\begin{aligned} &\sum_{j=1}^{n} \lambda_j X_j + S^- = \theta X_{j_0} \\ &\sum_{j=1}^{n} \lambda_j Y_j - S^+ = Y_{j_0} \\ &\lambda_j \geqslant 0, S^- \geqslant 0, S^+ \geqslant 0 \end{aligned}\right\} \tag{2}$$

where f(θ) is the objective function; θ is the comprehensive efficiency; λ_j is a set of linear programming solutions for the j^{th} DMU; $e_m=(1,1,...,1)^T \in R^m$ and $e_s=(1,1,...,1)^T \in R^s$ are m and s-dimensional unit vectors; respectively; $R^m$and R^s are m and s-dimensional vector spaces, respectively $X_j=(x_{1j}, x_{2j},..., x_{mj})$; $x_{1j}, x_{2j},..., x_{mj}$ are the m input indicators of the j^{th} DMU; $Y_j=(y_{1j}, y_{2j},..., y_{sj})$; $y_{1j}, y_{2j},..., y_{sj}$ are the s output indicators of the j^{th} DMU; ε is a non-Archimedean infinitesimal quantity,swhich is generally taken to be 10^{-6}; S^- and S^+ are the slack variables; X_{j0} and Y_{j0} are the vectors of inputs and outputs indicators of the j^{th} DMU, respectively.

The greater the θ value of DMU, the greater the input-output efficiency, i.e. the greater the efficiency of outputs obtained with the existing level of inputs. $\theta=1$ indicates the DMU is efficient; $\theta\neq1$ indicates that the DMU is inefficient.

Let D denote the original index set of the evaluation system; D_i is the re-constructed index set after removing the ith index in D; $\theta_j(D)$ and $\theta_j(D_i)$ denote the comprehensive efficiency value of the j^{th} DMUj under the index sets D and D_i, respectively. Then, $S_j(i)$ is the integrated efficiency index of DMUj under the indicator set D_i and is expressed as follows:

$$S_j(i) = \frac{\theta_j(D) - \theta_j(D_i)}{\theta_j(D_i)} \quad j = 1,2,\ldots,n \tag{3}$$

For the relatively inefficient DMU$_k$, if the i_0^{th} indicator satisfies $S_k(i_0)=\min S_k(i)$, then it indicates that the i_0^{th} indicator has the most influence on the inefficiency of DMU$_k$. When this indicator represents inputs, it means that the inputs corresponding to the i_0^{th} indicator are too large or too inefficiently used; when this indicator represents outputs, it means that the outputs corresponding to the i_0^{th} indicator are too small.

Evaluation system construction

Among eye movement indicators, the higher the observational perception efficiency and the smaller the cognitive load of pedestrians, the smaller the total duration of fixation, the number of fixation, the number of saccades, the average peak speed of saccades, the average amplitude and total amplitude of saccades. Moreover, the smaller the degree of visual fatigue of pedestrians, the smaller the average pupil diameter. Among the physiological indicators, the more stable the pedestrian's mood or the lower the psychological pressure, the smaller the average growth heart rate, the smaller the SDNN and the EDR amp. The smaller the EDR amp., the larger the EDR rit.; the weaker the degree of visual fatigue, the smaller the LF, the larger the HF and the smaller the LF/HF. In order to explore the differences in the cognitive load between elderly and young pedestrians waiting to cross the street, seven eye-movement indicators were used as input indicators and seven physiological indicators were used as output indexes. The cognitive load of each DMU was evaluated with the value of the observational perception efficiency as a reference, and the final evaluation indicator system is shown in *Figure 3*.

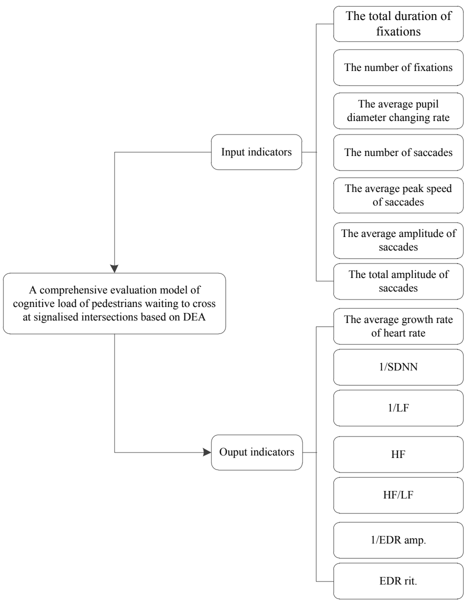

Figure 3 – Comprehensive evaluation indicator system of cognitive load of pedestrians waiting to cross the street at signalised intersections

3. RESULTS AND DISCUSSION

3.1 DEA results

This study investigated the significance of the differences in the eye movement and physiological indexes of pedestrians at different ages and in different scenes, including the different signal colour, cutdown time and other static traffic facility. The Shapiro-Wilk test shows that all the data did not conform to the normal distribution ($P<0.05$). Thus, the Mann-Whitney U test in the nonparametric test method was used to test the differences in the data of each group, and the results are shown in *Table 3*. *Table 3* shows that the differences in all indicators (except for LF/HF) between the elderly and young pedestrians at different ages under the same scene were significant. This indicates that in the same scene, the elderly and young pedestrians exhibited different visual and mental loads. In contrast, there were no significant differences in each indicator in different scenes. Considering that Scene A was more common in Chongqing, China, the experimental data of Scene A were selected for subsequent analysis. Each subject was treated as a separate DMU, totalling 60 DMUs. The input and output indicators of all DMUs were summarised and substituted into the DEA-CCR model to obtain the observational perception efficiency values θ of each DMU (*Table 4*).

Table 3 – Results of variance test

Indicators	Scenario difference		Age difference	
	Z	P	Z	P
Total duration of fixations	-1.597	0.110	-4.180	0.000***
Number of fixations	-1.262	0.207	-2.570	0.010***
Average pupil diameter changing rate	-1.084	0.278	-6.420	0.000***
Number of saccades	-1.282	0.200	-4.436	0.000***
Average peak speed of saccades	-1.494	0.135	-3.880	0.000***
Average amplitude of saccades	-1.603	0.109	-5.195	0.000***
Total amplitude of saccades	-1.455	0.146	-5.545	0.000***
Average growth rate of heart rate	-0.890	0.374	-2.044	0.041*
SDNN	-0.500	0.617	-2.356	0.018*
LF	-1.474	0.140	-5.093	0.000***
HF	-0.650	0.516	-2.284	0.022*
LF/HF	-0.152	0.879	-1.205	0.228
EDR amp.	-0.232	0.816	-1.700	0.049*
EDR rit.	-0.385	0.700	-1.875	0.035*

*Note: * is p<0.05, ** is p<0.01, and *** is p<0.001, indicating significant differences.*

Table 4 – Observation of perceptual efficiency evaluation results of DMU in Scenario A

DMU	Efficiency values θ	Pedestrian categories	θ mean	Mean after removing θ = 1	Number of valid DMUs
1	0.517	Elderly pedestrians	0.835	0.738	11
2	1				
…	…				
29	0.693				
30	0.664				
31	0.723	Young pedestrians	0.922	0.833	16
32	1				
…	…				
59	0.937				
60	1				

3.2 Efficiency analysis

Table 4 shows that if the observational perception efficiency is 1, then the subject has high cognitive efficiency in the scene and is DEA-efficient; if the observational perception efficiency is less than 1, then the subject has low cognitive efficiency in the scene and is DEA-inefficient. Overall, in the same crossing scene, the average observational perception efficiency values of the elderly and young pedestrians were 0.835 and 0.922, respectively. A total of 16 young pedestrians had an observational perception efficiency value of 1 in Scene A, and there were 11 DEA-efficient elderly people. This indicates that the overall perceptual efficiency of the elderly pedestrians was lower than that of the young pedestrians. In terms of the DMU with an observational perception efficiency value less than 1, the elderly pedestrians (0.738) had a lower average efficiency value than the young pedestrians (0.833). The results show that, in the same waiting scene, the cognitive load of the elderly pedestrians was higher than that of the young pedestrians. This indicates that under the condition of receiving the same external information, the observational perception efficiency of the elderly pedestrians was lower than that of the young pedestrians. This means the elderly pedestrian need longer time to deal with the information, and the efficiency and accuracy is lower than in young people, which makes it more difficult for them to deal with dangerous information in a timely and accurate manner in the traffic environment. Moreover, for the DEA-efficient DMUs (i.e. those with lower observational perception efficiency), the cognitive load of elderly pedestrians was significantly higher than that of the young pedestrians. Therefore, optimising traffic facilities can reduce the difficulty of the elderly pedestrians in extracting key information in the traffic environment. Lowering the cognitive load of elderly pedestrians enables elderly pedestrians to perceive the risk factors in the traffic environment more rapidly, thus effectively improving the safety of the elderly pedestrians waiting to cross the street.

3.3 Analysis of cognitive load variability

In order to investigate the causes of the above differences in the cognitive load, the radial distance between each DMU and the objective function under the influence of each slack variable was calculated. Then, the direction and magnitude of improvement of each slack variable were obtained in order to achieve the DEA efficiency. The results of the analysis of the slack variables are shown in *Table 5*.

It was found that none of the slack variables of the DMUs located in the frontier plane and with an efficiency value of 1 needed to be adjusted. In contrast, there were differences in the magnitude of changes in the slack variables of the other DMUs. This indicates that different factors in the external environment contributed to the differences in physiological loads of the pedestrians. In order to achieve DEA efficiency, the three slack variables (i.e. average pupil diameter changing rate, average peak saccade speed and average saccade amplitude) of the DEA-inefficient DMUs in both pedestrian categories needed to be adjusted by less than 10%. This indicates that these three variables had fewer impacts on the variability of the cognitive load of the elderly and young pedestrians when waiting to cross the street.

The analysis of eye movement indicators shows that the two slack variables (total amplitude and number of saccades) were greater in the elderly pedestrians than in the young pedestrians. This indicates that in the same environment, the elderly pedestrians perceived the information of the traffic environment as more complex, with longer perceptual reaction time, i.e. it was more difficult for them to perceive the observed information. In addition, the decrease in the sum of fixation durations of the elderly group (35.20%) was larger than that of the young group (26.21%). The number of fixations decreased by 35.78% for the elderly group, which was smaller than that of the young group (43.94%). This suggests that the elderly pedestrians had fewer fixation times on the target of interest with longer durations, indicating that the elderly pedestrians had more difficulties with perceiving the information. In terms of ECG, in the same scene, the average changes of the average growth rate of heart rate, SDNN, LF, HF and LF/HF of the corresponding pedestrians were analysed (*Table 4*). *Table 4* shows that the average changes in the slack variables of most HRV indicators of the elderly pedestrians were greater than those of the young pedestrians. Overall, the cognitive load of the elderly pedestrians was larger than that of the young pedestrians. The changes in the LF and LF/HF of the elderly pedestrians were larger than that of the young pedestrians. This indicates that the elderly pedestrians were subjected to larger cognitive loads, and sympathetic and vagal homeostasis were more difficult to maintain in the elderly pedestrians when confronted with the stimuli. In terms of EDA variability, EDRs varied greatly between individuals for the elderly group, and the average changes in the slack variables of the EDA indicators were larger than those of the younger group. Thus, in the same scene, although the elderly pedestrians showed significantly lower efficiency overall than the young pedestrians, they were more sensitive to external stimuli.

Table 5 – Magnitude of variation of slack variables

Slack variables		Elderly pedestrians [%]					Elderly pedestrians mean [%]	Young pedestrians [%]					Young pedestrians mean [%]
		1	2	…	29	30		31	32	…	59	60	
S^-	Total duration of fixations	-21.12	—	…	—	-45.03	-35.20	—	—	…	-1.22	—	-26.21
	Number of fixations	-53.51	—	…	-6.65	-47.68	-35.78	—	—	…	—	—	-43.94
	Average pupil diameter changing rate	—	—	…	-4.58	—	-5.54	—	—	…	—	—	-2.41
	Number of saccades	-57.58	—	…	-21.00	-55.15	-35.40	-3.62	—	…	—	—	-28.99
	The average peak speed of saccades	—	—	…	—	—	-5.18	-7.98	—	…	—	—	-8.23
	Average amplitude of saccades	—	—	…	—	-1.57	-11.58	—	—	…	—	—	-1.65
	Total amplitude of saccades	-76.12	—	…	-35.69	-73.66	-50.84	-19.96	—	…	-6.34	—	-33.90
S^+	Average growth rate of heart rate	—	—	…	—	—	45.57	339.74	—	…	35.79	—	247.38
	SDNN	—	—	…	49.88	0.35	34.45	150.93	—	…	140.31	—	119.14
	LF	2 684.92	—	…	57.06	1 434.14	866.09	259.66	—	…	325.27	—	261.25
	HF	1 799.12	—	…	—	939.68	900.87	39.63	—	…	503.50	—	372.09
	LF/HF	35.70	—	…	17.54	—	331.72	144.55	—	…	—	—	85.38
	EDR amp.	129.19	—	…	—	6 616.69	1159.50	779.24	—	…	39.25	—	850.05
	EDR RIT.	440.31	—	…	3 970.36	6 669.62	2273.44	41.08	—	…	84.19	—	406.09

3.4 Sensitivity analysis

In order to further explore the influence of each indicator on the observational perception efficiency of the two pedestrian groups, the pedestrian observational perception efficiency indexes after removing each index were summed to get the sensitivity of each index. The results are shown in *Table 6*. The larger the sum of the indexes, the greater the change in the efficiency value after removing the index, i.e. the greater the impact of the index on the observational perception efficiency.

Table 6 – Total comprehensive efficiency index of pedestrian observation and perception in Scenario $A\sum S_j(X_i)$

Pedestrian categories	$\sum s_j(X_1)$	$\sum s_j(X_2)$	$\sum s_j(X_3)$	$\sum s_j(X_4)$	$\sum s_j(X_5)$	$\sum s_j(X_6)$	$\sum s_j(X_7)$	$\sum s_j(Y_1)$	$\sum s_j(Y_2)$	$\sum s_j(Y_3)$	$\sum s_j(Y_4)$	$\sum s_j(Y_5)$	$\sum s_j(Y_6)$	$\sum s_j(Y_7)$
Elderly pedestrians	1.379	0.220	0.013	0.000	1.559	0.000	0.356	1.764	0.243	0.111	0.026	0.432	0.226	1.305
Young pedestrians	2.270	0.260	0.009	0.039	0.759	0.000	1.228	0.293	0.006	0.000	0.106	0.471	0.360	0.490

Note: X=(X1,X2,X3,X4,X5,X6,X7)=(the total duration of fixations, the number of fixations, the average pupil diameter changing rate, the number of saccades, the average peak speed of saccades, the average amplitude of saccades and the total amplitude of saccades), Y=(Y1, Y2, Y3, Y4, Y5, Y6, Y7)=(the average growth rate of heart rate, SDNN, LF, HF, LF/HF, EDR amp., EDR rit.)

The output indicators of the cognitive load evaluation system for pedestrians waiting to cross the street (*Table 6*) indicate that in the young group, the combined efficiency indexes of the total saccade amplitude and the fixation duration showed the largest impacts on the cognitive load, and the HRV indicators showed almost negligible impacts. In the elderly group, the average growth of heart rate, the average peak saccade speed, the total fixation duration and EDR rit. exhibited a larger influence on the cognitive load. This indicates that elderly pedestrians had more complex and intense responses to external stimuli, and their cognitive processes were accompanied by more sensory invocations. These directly led to a higher cognitive load in the same scene. In addition, the combined efficiency index of the average pupil diameter and saccade amplitude of the two types of pedestrians was close to 0, indicating that these two indicators had insignificant impacts on the observational perception efficiency. It can be assumed that the two types of pedestrians paid attention to static or dynamic information to the same extent when observing and perceiving the traffic environment. However, the combined efficiency index of the sum of the fixation durations for the elderly pedestrian was higher. This may be because it is more difficult for the elderly to extract key information in the traffic environment.

4. CONCLUSIONS AND DISCUSSION

The previous research had certain limitations in analysing the elderly pedestrian eye movement and physiological response when waiting to cross the intersection. Some of them found that the elderly had been nervous and made the wrong decision [3]; some of them found the adults would spend more time observing the useful information [6]; Tapiro et al. [7, 8] found that the elderly pedestrians would spend more time observing the traffic condition in the middle of the road. Some researchers analysed the relationship between the physiology indicators and the cognitive load, but they did not consider the vision parameters [15–18]. Furthermore, there is few research on the elderly pedestrians. In order to analyse the cognitive load differences between the elderly and young pedestrians when waiting to cross the intersection under the same traffic scene, the typical eye movement and physiological indicators characterising the cognitive load of pedestrians were used to construct a comprehensive evaluation model of the cognitive load of pedestrians waiting to cross the street based on the DEA. Then, the causes of the differences in the cognitive loads of the two pedestrian groups in the same scenarios were analysed. The main conclusions are as follows:

1) A total of 16 young people and 11 elderly people had DEA-efficient observational perception efficiency in Scene A, indicating that the overall observation-perception efficiency of elderly pedestrians was lower than that of young pedestrians in the same street-crossing scene.
2) Compared with young pedestrians, elderly pedestrians showed smaller total visual durations and fixation numbers while waiting to cross the street, indicating that it is more difficult for elderly people to perceive relevant information. In the same traffic scene, elderly pedestrians perceived the traffic environment as more complex and required longer reaction time.
3) In terms of ECG, the slack variables of most HRV indicators of elderly pedestrians were larger than those of young pedestrians, such as LF and LF/HF. This indicates that elderly pedestrians had larger cognitive loads than young pedestrians. It was more difficult for elderly pedestrians to maintain sympathetic and vagal homeostasis when facing the same stimuli in the same crossing scene.

Moreover, there are some aspects should be researched in the future:

1) This experiment collected eye movement and physiological data from the old and young people while waiting at the crossing, but the number of valid samples for those aged 70 and above was relatively small, and the sample size of senior elderly volunteers should be increased. Meanwhile, since the eye movements and physiological and psychological characteristics of older pedestrians in different age groups may vary greatly while waiting to cross the street at signalised intersections, the classification of old pedestrians will be refined in subsequent studies, i.e. the elderly should be classified into low- and high-aged old pedestrians based on their age for corresponding analyses.
2) The paper compared the cognitive load difference between the old and young people when waiting to cross the signalised crosswalk. It was found that the old people need more time to respond to the traffic

information, and the precision is lower than in the young people. Thus, the traffic facility setting and design should consider this condition, especially for the living area of elderly people. How to make these improvements is another aspect that needs to be researched in future.

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REFERENCE

[1] Traffic management research institute of the ministry of public security. Annual report of traffic accident statistics of the people's republic of China (2020). *Traffic Management Research Institute of the Ministry of Public Security*. Report number: 2020.

[2] Trpković A, et al. The crossing speed of elderly pedestrians. *Promet-Traffic & Transportation*. 2017;29(2):175-183. DOI: 10.7307/ptt.v29i2.2101.

[3] Webb EA, et al. Crossing the road in time: Inequalities in older people's walking speeds. *Journal of Transport & Health*. 2017;5(2):77-83. DOI: 10.1016/j.jth.2017.02.009.

[4] Lan LT, et al. Evaluation of conflict severity between pedestrians and right-turning vehicles. J*ournal of Chongqing University of Technology (Natural Science)*. 2022;36(7). http://clgzk.qks.cqut.edu.cn/CN/Y2022/V36/I7/70 [Accessed 17th Aug. 2022].

[5] Jain A, Gupta A, Rastogi R. Pedestrian crossing behaviour analysis at intersections. *International Journal for Traffic and Transport Engineering*. 2014;4(1):103-116. DOI: 10.7708/ijtte.2014.4(1).08.

[6] Biassoni F, et al. Visual exploration of pedestrian crossings by adults and children: Comparison of strategies. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2018;56(7):227-235. DOI: 10.1016/j.trf.2018.04.009.

[7] Tapiro H, Oron-Gilad T, Parmet Y. Pedestrian distraction: The effects of road environment complexity and age on pedestrian's visual attention and crossing behavior. J*ournal of Safety Research.* 2020;72(12):101-109. DOI: 10.1016/j.jsr.2019.12.003.

[8] Tapiro H, et al. Where do older pedestrians glance before deciding to cross a simulated two-lane road? A pedestrian simulator paradigm. *The Human Factors and Ergonomics Society Annual Meeting*, 19-23 Sept. 2016, Los Angeles, USA. 2016. p. 11-15. DOI: 10.1177/1541931213601003.

[9] Zeeger CV, et al. Analysis of elderly pedestrian accidents and recommended countermeasures. *Transportation Research Record*. 1996;27(2):56-63. DOI:10.1016/0022-4375(96)86964-7.

[10] Dommes A, Cavallo V, Oxley J. Functional declines as predictors of risky street-crossing decisions in older pedestrians. *Accident Analysis & Prevention*. 2013;59(10):135-143. DOI:10.1016/j.aap.2013.05.017.

[11] Oxley J, Fildes BN, Ihsen E. Older pedestrian safety: The role of perceptual and cognitive factors and the ability to compensate for age-related changes. *Proceedings of the Australasian road safety research, policing and education conference, Monash University*. 2000. p. 209-215.

[12] Dommes A, et al. Age-related differences in street-crossing safety before and after training of older pedestrians. *Accident Analysis & Prevention*. 2012;44(1):42-47. DOI:10.1016/j.aap.2010.12.012.

[13] Sun CY. *Theoretical and empirical research on cognitive load*. Liaoning, CN: Liaoning People's Publishing House; 2014.

[14] Lee Y, Lee JD, Boyle LN. The interaction of cognitive load and attention-directing cues in driving. *Human Factors.* 2009;51(3):271-280. DOI: 10.1177/0018720809337814.

[15] Mikula L, et al. Eye-head coordination and dynamic visual scanning as indicators of visuo-cognitive demands in driving simulator. *PloS One*. 2020;15(12):1-21. DOI: 10.1371/journal.pone.0240201.

[16] Ahn JW, Ku Y, Kim HC. A novel wearable EEG and ECG recording system for stress assessment. *Sensors*. 2019;19(9):1991-1991. DOI: 10.3390/s19091991.

[17] Barua S, Ahmed MU, Begum S. Towards intelligent data analytics: A case study in driver cognitive load classification. *Brain Sciences*. 2020;10(8):1-19. DOI: 10.3390/brainsci10080526.

[18] Bailey BP, Iqbal ST. Understanding changes in mental workload during execution of goal-directed tasks and

its application for interruption management. *ACM Transactions on Computer-Human Interaction (TOCHI)*. 2008;14(4):1-28. DOI: 10.1145/1314683.1314689.

[19] Liu X. Measuring cognitive load level based on eye movement data. PhD thesis. Southwest University; 2017.

[20] Liu X, Wang H-Z. Research on security check visual search based on image saliency. *Journal of Chongqing University of Technology (Natural Science)*. 2019;33(5). http://clgzk.qks.cqut.edu.cn/CN/Y2019/V33/I5/84 [Accessed 17th Jul. 2019].

[21] Liang GH, et al. Evaluating the influence of approaching vehicles on pedestrian's visual patterns and crossing behaviors at an uncontrolled crosswalk. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2022;88(5):236-247. DOI: 10.1016/j.trf.2022.05.026.

[22] Lanzer M, et al. Assessing crossing and communication behavior of pedestrians at urban streets. *Transportation Research Part F: Traffic Psychology and Behaviour*. 2021;80(2):341-358. DOI: 10.1016/j.trf.2021.05.001.

[23] Bianchi LJ, Kingstone A, Risko EF. The role of cognitive load in modulating social looking: a mobile eye tracking study. *Cognitive Research Principles and Implications*. 2020;5(1):44. DOI: 10.1186/s41235-020-00242-5.

[24] Zhu P, Chang RS. Effects of gender and situational hazard level on pedestrian hazard perception: Evidence from ERP. *Studies of Psychology and Behavior*. 2020;18(1). https://psybeh.tjnu.edu.cn/CN/Y2020/V18/I1/113 [Accessed 20th Jan. 2020].

[25] He XM, Li JY. Cause analysis and design strategies of cognitive load in human-computer interaction. *Packaging Engineering*. 2020;41(10):24-30. DOI: 10.19554/j.cnki.1001-3563.2020.10.005.

[26] Xu ZM, et al. A review of cognitive workload assessment based on EEG. *Space Medicine & Medical Engineering*. 2021;34(4):339-348. DOI: 10.16289/j.cnki.1002-0837.2021.04.008.

[27] Marquart G, Cabrall C, Winter J. Review of eye-related measures of drivers' mental workload. *Procedia Manufacturing*. 2015;3(7):2854-2861. DOI: 10.1016/j.promfg.2015.07.783.

[28] Hutt S, et al. Automated gaze-based mind wandering detection during computerized learning in classrooms. *User Modeling & User Adapted Interaction*. 2019;(1). DOI:10.1007/s11257-019-09228-5.

[29] Wei QL. Data envelopment analysis (DEA). *Chinese Science Bulletin*. 2000;45(17):1793-1808. DOI: 10.1360/csb2000-45-17-1793.

[30] Song MH. *Research on the evaluation of Beijing rail transit operation efficiency based on DEA*. PhD thesis. Beijing Jiaotong University; 2017.

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信号交叉口老年人-年轻人等待过街的认知负荷差异性评价

摘要

行人认知负荷对行人过街决策具有重要影响。相比年轻人，老年人身体功能衰退，且反应能力也减弱，这使得他们在过街时更容易产生事故。为对比分析老年人和年轻人在信号交叉口等待时的视觉信息-心理负荷的关联关系，并对认知负荷的差异性进行评价，选取中国重庆市南岸区2个不同交通设计的信号交叉口，利用眼动仪、生理仪采集年轻人和老年人的眼动、心电、皮电等数据，以视觉指标（视点持续时间总和、注视次数、平均瞳孔直径变化率、扫视次数、扫视平均峰值速度、扫视的平均振幅和扫视总幅度为眼动视觉指标）为输入，以生理指标（心率增长率均值，心率变异性时域分析指标，HRV频域分析指标，皮电反应峰值、皮电峰值到达时间为生理指标）为输出，基于数据包络分析方法，构建了行人等待过街认知负荷综合评价模型，进而对比分析了老年人和年轻人在等待过街时认知负荷特征。结果显示：在同样的过街场景下，老年人的整体感知效率低于年轻人，且视觉持续注视时间和次数均低于年轻人，认知负荷高于年轻人。研究成果可以为提升老年人过街安全性研究提供相应的参考。

关键词

交通安全；行人过街；认知负荷；数据包络分析；眼动实验；生理实验