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Evaluation of Novel Cognitive Assessment System for Testing Visual Memory of the Elderly

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ABSTRACT With the development of such technologies as embedded systems, cloud databases and hardware components, detection of cognitive in the elderly can be made more convenient and accurate. This work develops a novel cognitive assessment interactive embedded system, which consists of a micro-controller unit (MCU), organic light-emitting diode (OLED) modules and a client identification circuit. The reliability of the proposed system is demonstrated in visuospatial memory tests. With its combination of OLED modules and pressable components, the elderly can use the system to perform testing under a flashing light source sequence with tactile feedback. To identify the various pattern arrangements in the Corsi block tapping task (CBTT), the client identification circuit in the proposed system is implemented to compute the number of OLED lighting devices on each column of the wooden base. The data that are collected from each subject will be transferred to cloud servers through a smart phone APP via wireless networks to eliminate recording errors by the experimenter. The functionality of the spatial working memory is verified in experiments that involve the proposed OLED, a computerized version of the CBTT, and 24 participants. Experimental results reveal that the difference in memory span between young and elderly groups is significant, $F(1, 92) = 214$, $p<0.001$, indicating the feasibility of the proposed system in spatial working memory detection.

INDEX TERMS Corsi block tapping task, spatial working memory.

I. INTRODUCTION

Dementia is a brain disease greatly affecting the behavior of the elderly which cannot be cured through pharmaceutical drug treatment [1]. Therefore, detection of Mild Cognitive Impairment (MCI), the early stage of dementia, has been proven to be one way to reduce the progress of the disease. The Mini-Mental State Examination (MMSE) is a common method to clinically assess cognitive ability and thereby identify subjects with dementia [2]–[5]. However, MMSE relies greatly on verbal tasks and cannot assess visual abilities and executive functions; as such, it is only weakly sensitive to MCI [5]. Therefore, the Corsi block tapping task (CBTT) is used to assess visuospatial working memory and spatial attention [6]. This task has been widely used in both early dementia detection in clinical practice and in experimental research into cognitive impairment that is caused by brain lesions [7]–[11]. The CBTT is a span task in which neuropsychologists place nine wooden cubes on a board to assess cognitive status. The subject is asked to observe and re-tap the cube sequence demonstrated by experimenter. Finally, performance as an assessment of cognitive ability is evaluated by recording the longest correctly measured sequence wherein the subject repeats increasingly complex visuospatial patterns and movement sequences. However, the fact that traditional CBTT lacks management standards and has human processing errors, or has omissions in its records, makes the validity and reliability of the assessment questionable [12]–[14]. To solve

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the problem of human errors in traditional CBTT, a computer-based version of CBTT was developed [14]–[19]. Claessen *et al.* compared the performance of memory span in manual and automatic systems using traditional and computerized CBTT [15]. The results confirm that no significant differences exist in the subjects' performance between the two versions and highlight the benefits of precise measurement using the computerized system. Although the computer-based CBTT system is extremely easy to operate and can accurately record data without human error, the system operates under a 2-dimensional plane instead of a 3-dimensional space, which renders the elderly less intuitive when performing CBTT and leads to instability of the results. Perrochon *et al*. proposed another modified walking Corsi test (MWCT) method to explore the spatial orientation in elderly subjects through a navigation task [17]. This method uses force sensors to detect a subject's walking path and records the relevant data at a computer workstation. However, this system requires a large space and is complicated to install. Moreover, the elderly are prone to be confused by excessively complex paths, leading to a decay in detection accuracy.

This work proposes an organic light-emitting diode (OLED) display-based system to provide information to psychologists about a subject's visuospatial short-term working memory. The system is designed with a micro-controller unit (MCU) and Bluetooth transceiver to enable it automatically to score and record experimental results, eliminating human errors in measurements. The proposed OLED lighting devices, which can be arbitrarily stacked, are equipped with a tactile feedback switch and a pattern recognition circuit to facilitate their operation by the subject. When an elderly person finishes a task, the system instantly uploads data to the established cloud server through a wireless network and simultaneously generates forms and charts daily to provide test results for further evaluation by a psychologist. The simplicity of the operating procedure gives the experimenter sufficient time to observe the behavior of the subject while performing the task. The system parameters can be customized to assess further cognitive state based on various CBTT performance results. An OLED display is suitable for the elderly whose eyes may have degraded, as its spectrum is similar to sunlight. The feasibility of the proposed system is verified from a memory span obtained in the CBTT. In an experiment with 24 participants, age significantly affected performance in the CBTT, showing that the proposed system is appropriate for assessing spatial working memory mechanisms. The average memory span of the elderly in the proposed system is 45.8% higher than that in the computer version, showing that the elderly can operate the proposed system more easily than the computer version.

II. DESIGN OF PROPOSED OLED LIGHTING SYSTEM

A novel interactive cognitive CBTT system for the elderly is shown in Fig. 1. The system adopts interactive OLED lighting devices to implement the CBTT and reduces human operating errors by using an embedded system that is composed of an MCU and a client identification circuit. Moreover, the collected data from each subject are uploaded to a cloud server via a wireless network to provide statistics and tabulation for cognitive evaluation by psychologists. The proposed system can be divided into hardware and software. It utilizes a psychological test that is similar to CBTT to evaluate the visuospatial short-term working memory.

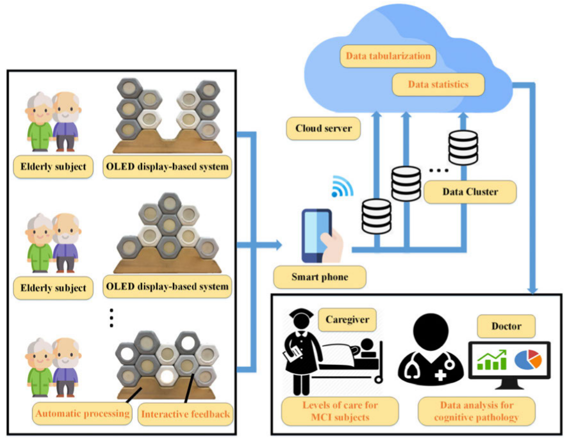


FIGURE 1. System architecture of cognitive scheme.

A. ARCHITECTURE OF PROPOSED SYSTEM

Fig. 2 shows a flowchart of the main components of the hardware, including an 8-bit AVR micro-controller unit (MCU, ATMEGA2560), an OLED light module (IWS1010SR-0) that is driven by an addressable OLED driver circuit, a constant current supply module (LM317), a shift register (SN74LS165), a micro switch (D2FC-F-7N), a Bluetooth module (HC-05) and a power supply module. The MCU is equipped with various I/O pins, including 54 digital pins of which 14 can be used as PWM signal pins, four UART pins, and five SPI pins; it is integrated with the other modules/components of the proposed system. Since sunlight is white light composed of various visible wavelengths, white light was used in this work to enhance the experience and comfort of users. OLEDs have advantages, including a wide viewing angle, low power consumption and high contrast. The OLED is a self-luminous device that can emit homogeneous light without glare and has a wide and continuous band range that is similar to that of sunlight, and is widely used in lighting applications [20]-[22]. The OLED light modules are operated under a constant current of 1 mA with a luminance of up to 1200 cd/m^2; the brightness is controlled using PWM technology. The OLED light modules are glare-free and the limit operating temperature is 40°, making it visible and touchable. Since the proposed system is designed with stackable devices, a simple circuit is used to count the devices in each column, as shown in Fig. 3. When the system is activated, the LM317 module generates a constant current, which is calculated from the reference voltage V_{ref} at the adjust pin and the self-design resistance R_{Adj}, using (1)

$$I = \frac{V_{ref}}{R_{Adj}} \tag{1}$$

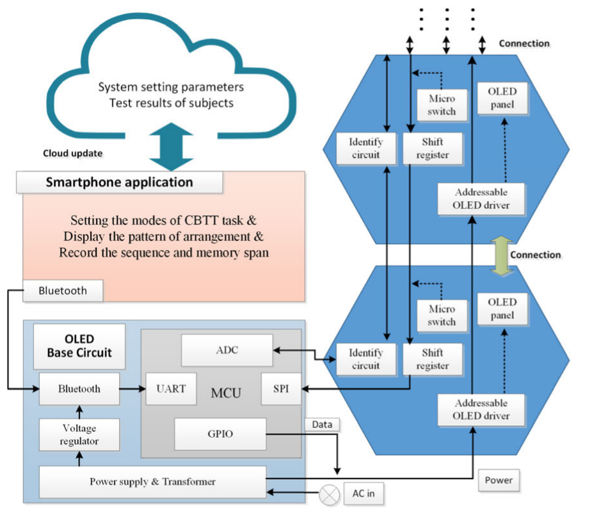


FIGURE 2. Proposed OLED display-based system.

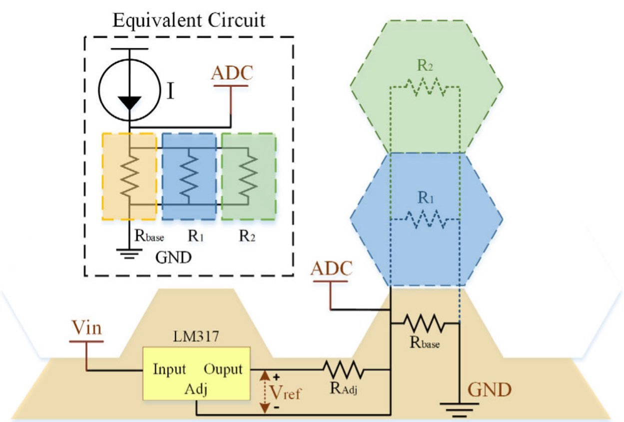


FIGURE 3. Current source-based client identification circuit.

Thus, the devices in the series change the voltage at the center pin and the ADC value is given by (2)

$$ADC = I \times R_{total} \times 2^n \tag{2}$$

where V_{in} is the analog voltage on the selected input pin; V_{ref} is the selected voltage reference; n is the number of ADC output bits; and R_{total} is the equivalent impedance on each column of the OLED lighting devices with the base resistor with resistance R_{base}. Since the OLED lighting device and R_{base} have the same impedance of R and the latter is driven by a constant current source, the equivalent impedance in each column can be expressed as (3)

$$R_{total} = \frac{1}{(K+1) \times \frac{1}{R}} = \frac{R}{K+1} \tag{3}$$

where K is the number of OLED lighting devices in each column and can be obtained from (2) and (3) as in (4).

$$K = \frac{1 \times R \times 2^n}{ADC} - 1 \tag{4}$$

After the K value of each column has been obtained, the MCU can encode and transmit these data to a smart phone

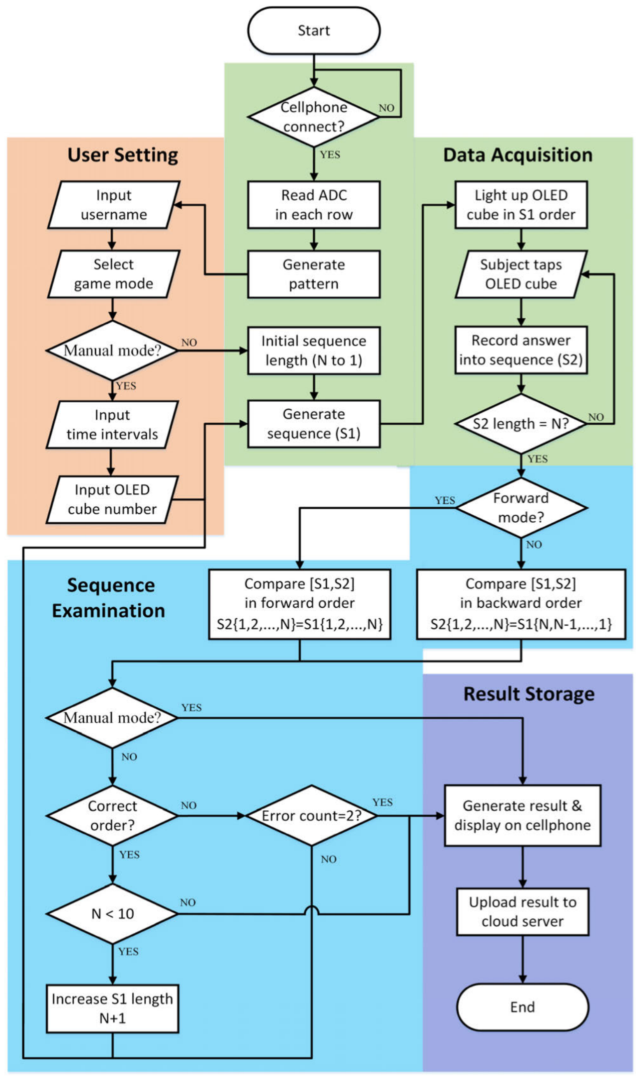


FIGURE 4. Flowchart of proposed scheme for CBTT and data transmission, comprising four stages: user setting; data acquisition; sequence examination; and result storage.

APP using Bluetooth. To turn on the OLED lighting devices in a specified sequence, the MCU commands the OLED driver to convert the data signal into constant current source signals and then sends these signals to illuminate the OLED light modules in sequence. Next, when the subject starts to perform the task and taps the OLED lighting devices in the sequence that he or she has memorized, the micro switch will be triggered and the signal is then input to a shift register. The result will be sent to the MCU through the SPI interface when the task is finished. Simultaneously, the MCU commands Bluetooth to transmit the result data, including the block span or task time, to the smart phone through UART.

B. SYSTEM FIRMWARE AND PROCEDURE

To complete interactive processing, firmware was developed to be implemented in the MCU. Fig. 4 shows the firmware flowchart of the proposed OLED display-based system. When the program is activated, the system will check whether the APP has successfully connected to the MCU. If it

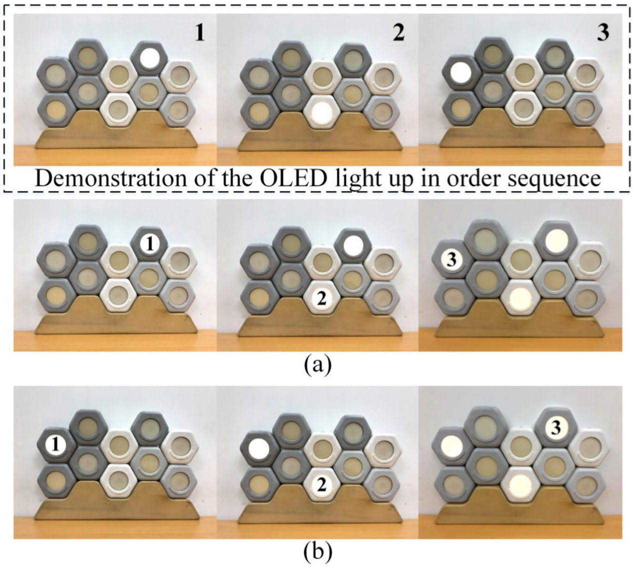


FIGURE 5. Tapping sequence in CBTT in different modes. (a) Forward mode (b) Backward mode.

has, then a pattern that corresponds to the arrangement of the OLED lighting modules will be exported to the smart phone. The experimenters then help the subject enter his or her personal information and select the test mode. The selected mode may be the forward mode or backward mode, which are both commonly used in the traditional CBTT, and a manual test mode allows the adjustable parameters to be modified. The details of the three modes are described as follows.

- Forward mode: In forward mode, the process is similar to CBTT; subjects are asked to observe a sequence of flashes by hexagonal OLED lighting devices. The initial sequence length is set to one and the flashing time is set to one OLED lighting device per second. The subjects have to tap the hexagonal OLED lighting devices in the same sequence after the flashing has finished.
- Backward mode: In backward mode, a sequence of flashing occurs as in forward mode, but the subjects are required to tap the flashing blocks in the reverse order. Fig. 5 schematically depicts both forward and backward modes.
- Manual test mode: In manual test mode, the experimenter can adjust the system parameters in each process, such as the length of the sequence, the customized sequence selection, and the flashing time of each OLED lighting device. This mode is usually suitable for explaining things to the disabled or to elderly individuals with poor comprehension skills.

After this mode is selected, the initial sequence length is set to N=1 and the system generates a sequence S1 of flashes of the OLED lighting devices. Next, the system checks whether the length of the recorded sequence S2 touched by the subject equals that of S1. The performance of the subjects in forward and backward modes is then calculated by the MCU. Finally, when a subject has completed the whole sequence of trials 1∼10 or has failed twice to remember a single sequence,

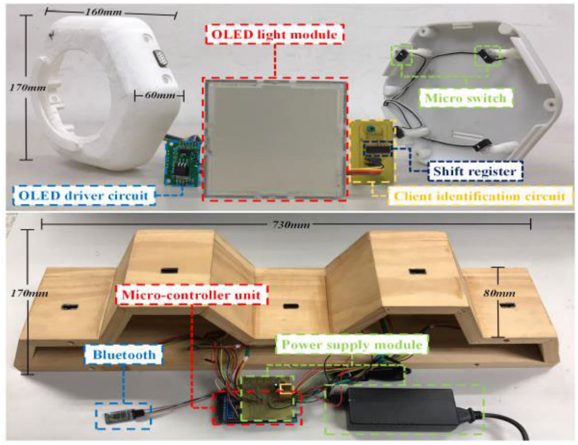


FIGURE 6. Components of OLED display-based system.

a chart of results is displayed on the smart phone. Meanwhile, the detailed test results, such as the location of each click, the numerical block span and the average time taken to recall each sequence, will be upload to a cloud server via WIFI for further analysis and discussion by psychologists.

III. RESULT AND DISCUSSION

A. PARTICIPANTS

Twenty-four subjects with a mean age of 55.3 years (SD = 30.3, range = 23 – 93), and a mean 12.7 years of education (SD = 7.89, range = 2 – 25) participated in this study. Subjects were divided into two groups—12 elderly people were recruited from a Geriatric Psychiatric Day Care Center and 12 healthy students were recruited from National Cheng Kung University. All subjects were healthy participants without neurological disease or any other diseases that is known to affect cognitive function. All experiments were approved by the Human Research Ethics Committee at National Cheng Kung University (NCKU HREC, Approval no. NCKU HREC-E-108-332-2). All subjects were provided written informed consent at the time of study participation, consistent with the Helsinki Declaration.

B. SYSTEM VERIFICATION

The real components of the OLED display-based system are configured with a wooden base (730mm×170mm×80mm) and ten hexagonal stackable OLED lighting devices (170mm×160mm×60mm), as shown in Fig. 6. To show how touch signals are transmitted from the OLED lighting devices to the microcontroller in the wooden base, Fig. 7 shows the timing diagram of the shift register during operation. The red line indicates the Master Input and Slave Output signals in the SPI interface, and the green line indicates the Serial Clock signal. Since the proposed system has an 8-bit shift register, the microcontroller receives eight values at a time, from which it determines whether a touch has occurred. Therefore, when the subject touches the OLED lighting devices, the micro switch will be triggered, and the slave output of the shift register generates an output of 0×01; otherwise, it outputs 0×00. The system is expandable and can be stacked into

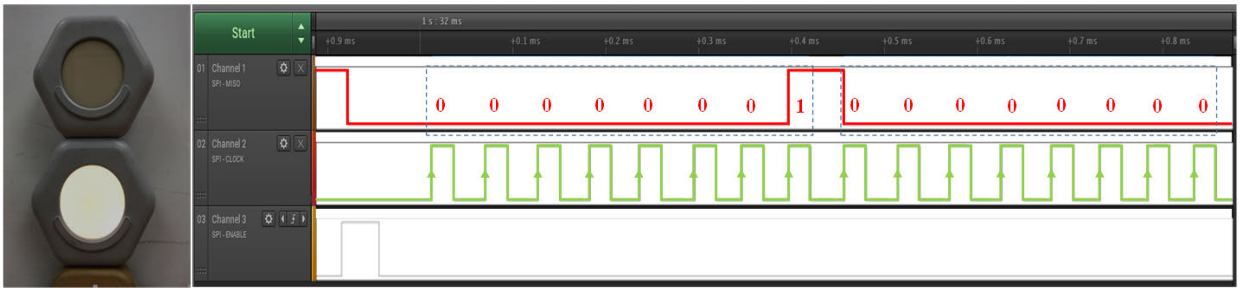


FIGURE 7. Timing diagram of SPI signal in proposed system for verification of OLED lighting and tapping sensing.

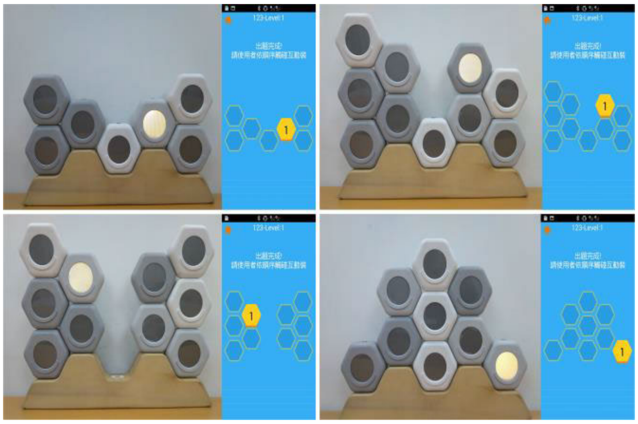
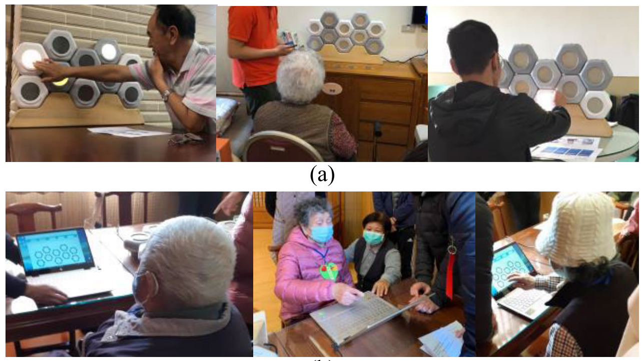


FIGURE 8. Arrangements of stackable OLED lighting devices and corresponding demonstrations on APP interface for smart phone.



(a)

(b)

FIGURE 9. Operating scenario of elderly subjects in proposed and computerized system. (a) proposed OLED system, (b) computerized system.

different arrangements to increase the diversity of possible tasks. Fig. 8 shows the different arrangements of the proposed system and the corresponding smart phone APP interface. The designed client identification circuits can effectively calculate the number of OLED lighting devices on each column and simultaneously display the corresponding pattern on the screen. By implementing the above touch position detection and pattern recognition functions, the visuospatial working memory can be experimentally measured.

C. RESULT ANALYSIS

To investigate the feasibility of the proposed OLED display-based system, a computerized CBTT was added to it and the performances of the subjects compared. The computerized version is developed using Matlab on a laptop computer (ASUS VivoBook TP412F; Intel Core i5 CPU 1.60 GHz; Windows 10 Professional), allowing the subjects to touch the screen to reduce the difficulty of operation. The system was administered in the same way as the proposed system, with a 1s flashing time and the same placement of the block. The only difference was that the subject was in front of a 2-dimensional 17'' screen (310 mm × 175 mm). Fig. 9 shows the operation scenario of the proposed and computerized version of CBTT. The collected data were analyzed using multifactorial ANOVA and the Mann-Whitney U test in the Statistical Package for the Social Sciences (SPSS), with a significance level of 0.05; Pearson correlation coefficients were also calculated. Table 1 shows the means and standard deviations of forward and backward spans for the computerized version and the proposed version of the CBTT. Table 2 presents the interaction results of two-way ANOVAs between age group and type of span (forward vs. backward) for all participants, and the gender and type of span for elderly participants. The interaction between age-group and type of span is not significant, $F(1, 92) = 0.11$, $p = 0.738$, but a significant main effect was observed in the age group, reflecting the lower memory span of elderly subject $F(1, 92) = 214$, $p<0.001$. A negative Pearson correlation was found between span and age ($r = -0.87$, $p < 0.001$), indicates that elderly subjects had worse spans than younger subjects. Another effect of type of span was significant, $F(1, 92) = 10.19$, $p=0.002$: the forward span was significantly longer than the backward span. This table also reveals that there was no significant interaction between gender and type of span for the elderly group, $F(1, 46) = 0.74$, $p = 0.786$. The significant main effects of gender, $F(1, 46) = 6.87$, $p = 0.012$, and type of span $F(1, 46) = 4.14$ $p = 0.048$, indicates that elderly females achieve longer spans than elderly males and that the elderly have a better span in forward mode. Fig. 10 compares the CBTT results obtained using the proposed OLED and the computerized CBTT for the elderly and young subjects. Table 3 provides the interaction results of two-way ANOVA between the two versions of the system and the type of span for the younger and elderly groups. The two versions exhibited without a significant main effect for young subjects, $F(1, 46) = 0.13$, $p = 0.725$, nor did it reveal interaction between two versions and type of span,

TABLE 1. Mean and standard deviation of span in forward and backward modes.

		Proposed System				Computer-based			
		Span FW		Span BW		Span FW		Span BW	
	n	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Elderly	12	4.00	1.21	3.17	1.02	2.75	1.22	2.17	0.94
Young	12	7.75	1.14	7.25	1.22	8.17	1.34	7.00	1.04
Female	9	4.78	1.39	3.89	1.05	4.33	2.45	3.77	2.54
Male	15	6.63	2.42	5.93	2.60	6.13	3.23	5.07	2.69
Young males	10	8.00	0.82	7.50	1.18	8.20	1.13	6.8	0.92
Elderly males	5	3.6	1.67	2.8	1.48	2.00	1.22	1.60	0.89
Young females	2	6.5	2.12	5.5	0.71	8.00	2.83	8.00	1.41
Elderly females	7	4.29	0.76	3.43	0.53	3.29	0.95	2.57	0.79
All participants	24	5.88	2.23	5.17	2.35	5.46	3.04	4.58	2.65

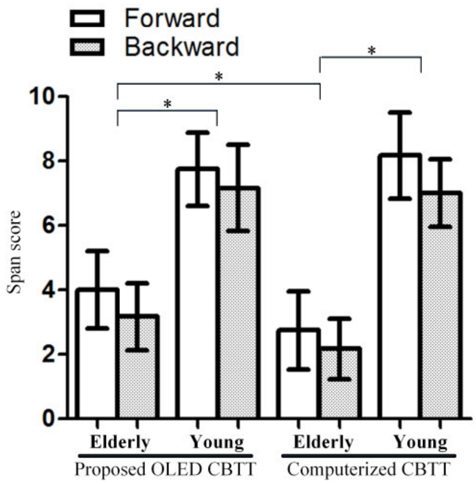


FIGURE 10. Average performance and standard deviation of span for each group based on proposed OLED and computerized CBTT.

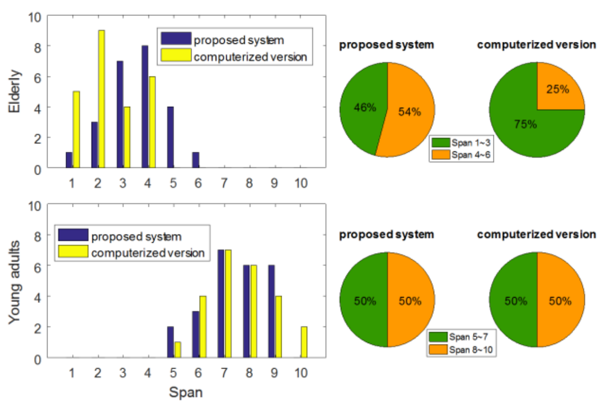


FIGURE 11. Span distribution for elderly and young subjects in terms of degree of visuospatial memory.

$F(1, 46) = 0.69$, $p = 0.412$. However, a significant main effect of the two versions was identified in the elderly group $F(1, 46) = 12.47$, $p = 0.001$, demonstrating that the span performance in the computerized CBTT was worse than that in the proposed OLED-based CBTT. To avoid the non-normal distribution that was associated with the smallness, the Mann-Whitney U test is used; this is a nonparametric test that compares two groups without assuming that their relevant values are normally distributed [23]. Table 4 presents the results of the Mann-Whitney U test on memory span in the elderly in

TABLE 2. Results (p-values) from two-way analyses of variance for age group and type of span.

Span in all data (p-value)		
Age group	Type of span	Age group × Type of span
0.000**	0.002*	0.738
Span in elderly data (p-value)		
Gender	Type of span	Gender × Type of span
0.012*	0.048*	0.786

*p < 0.05. **p < 0.001

TABLE 3. Results (p-values) from two-way analyses of variance for two versions of CBTT and type of span.

	Span in younger (p-value)	Span in elderly (p-value)
Versions	0.725	0.001**
Type of span	0.017*	0.031*
Versions × Type of span	0.412	0.697

*p < 0.05. **p < 0.001

light of gender and type of span. Significant effects were also found for both gender ($p=0.01$) and type of span ($p=0.002$), confirming the results for the elderly in table 2 and table 3. Fig. 11 displays the distribution of the visuospatial memory results for young adults and the elderly using the proposed system and the computerized CBTT. The pie charts illustrate that the performance of span in young adults are not affected by the two versions of CBTT. However, the number of the elderly with higher span performance (span 4∼6) rises from 25% to 54% when the proposed system is adopted. Moreover, the mean span performance using the proposed system is 45.8% better than that achieved using the computerized system for the elderly group, showing that the proposed system poses less of a problem for the elderly probably because the elderly have more difficulty than the younger group in operating the computer-based system. To validate the assertion that test results were accurate regardless of screen size, a 65" TV screen with an infrared touch outer frame was adopted to conduct the computerized CBTT. The mean span performance using the proposed system was 41.8%, better than that achieved using the computerized system on a large TV screen.

TABLE 4. MANN-WHITNEY U Test results for span score in the CBTT for male and female subjects.

Group (samples)	Sum of Ranks	Mann-Whitney U	p-value
Male (20)	371	161	0.01
Female (28)	805		
OLED version (24)	731	145	0.002
Computerized version (24)	445		

*p < 0.05. **p < 0.001

TABLE 5. Comparison between proposed and previously developed CBTT systems.

	Ref.[6]	Ref.[15]	Ref.[17]	This work
Automated data capture	X	○	○	○
User-defined arrangement of device	X	X	X	○
Shape of arrangement recognition	X	○	X	○
Realistic object interaction	○	X	○	○
Sensory feedback	X	Visual	Visual	Visual & Tactile
Interface for human-object interaction	Wooden Cube	LCD Touch Screen	LED under Carpet	OLED Cube

This results for a 65'' computerized CBTT reveal similar performance to that of a 17'' computerized CBTT, indicating that screen size is not a significant factor to affect this experiment. Table 5 compares the proposed OLED display-based system with a previously developed CBTT system [6], [15], [17]. An accurate digital recording by proposed system reduces human errors. Moreover, the flexibility offered by the customizable pattern or environmental parameter adjustments in the CBTT provides convenience and supports intuitive responses by to the experimenter and the subject. Also, based on the experimental results, the elderly subjects perform well with the interactive OLED lighting devices, showing that the proposed system is effective for use in visuospatial working memory tests.

IV. CONCLUSION

This work proposes a novel short-term visuospatial working memory test system based on an embedded system. The proposed system is easy to assemble and can be arbitrarily stacked to form a customized pattern for CBTT. The proposed system has advantages of more accurate span and reaction time measurement; it also provides the subject with a sequence and a touch feedback for the cognitive test by using the lighting devices and the micro switch. In an experiment, a significant p value ($p<0.001$) and strong Pearson correlation ($r=-0.87$) indicate that memory span declines with age. Furthermore, when 12 elderly subjects used the proposed OLED display-based system, the tested span was significant; $F(1,46) = 12.47$, $p = 0.001$ and achieves 45.8% better span results than the computerized CBTT. Therefore, the effectiveness of this system in assessing spatial cognitive functions is demonstrated.

REFERENCES

[1] A. Dragomir, A. G. Vrahatis, and A. Bezerianos, "A network-based perspective in Alzheimer's disease: Current state and an integrative framework," *IEEE J. Biomed. Health Informat.*, vol. 23, no. 1, pp. 14–25, Jan. 2019, doi: 10.1109/JBHI.2018.2863202.

[2] B. Wallace, F. Knoefel, R. Goubran, P. Masson, A. Baker, B. Allard, V. Guana, and E. Stroulia, "Detecting cognitive ability changes in patients with moderate dementia using a modified 'whack-a-mole' game," *IEEE Trans. Instrum. Meas.*, vol. 67, no. 7, pp. 1521–1534, Jul. 2018, doi: 10.1109/TIM.2017.2761638.

[3] Q. Zhou, M. Goryawala, M. Cabrerizo, J. Wang, W. Barker, D. A. Loewenstein, R. Duara, and M. Adjouadi, "An optimal decisional space for the classification of Alzheimer's disease and mild cognitive impairment," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 8, pp. 2245–2253, Aug. 2014, doi: 10.1109/TBME.2014.2310709.

[4] P. T. Trzepacz, H. Hochstetler, S. Wang, B. Walker, and A. J. Saykin, "Relationship between the Montreal cognitive assessment and mini-mental state examination for assessment of mild cognitive impairment in older adults," *BMC Geriatrics*, vol. 15, no. 1, pp. 107–115, Sep. 2015, doi: 10.1186/s12877-015-0103-3.

[5] J. W. Kim, D. Y. Lee, E. H. Seo, B. K. Sohn, Y. M. Choe, S. G. Kim, S. Y. Park, I. H. Choo, J. C. Youn, J. H. Jhoo, K. W. Kim, and J. I. Woo, "Improvement of screening accuracy of mini-mental state examination for mild cognitive impairment and non-alzheimer's disease dementia by supplementation of verbal fluency performance," *Psychiatry Invest.*, vol. 11, no. 1, pp. 44–51, Jan. 2014, doi: 10.4306/pi.2014.11.1.44.

[6] P. M. Corsi, "Human memory and the medial temporal region of the brain," Ph.D. dissertation, Dept. Psychol., ProQuest Inf. Learn., Ann Arbor, MI, USA, 1973.

[7] D. Stoffers, H. W. Berendse, J. B. Deijen, and E. C. Wolters, "Deficits on Corsi's block-tapping task in early stage Parkinson's disease," *Parkinsonism Rel. Disorders*, vol. 10, no. 2, pp. 107–111, Dec. 2003, doi: 10.1016/S1353-8020(03)00106-8.

[8] M. van Asselen, R. P. C. Kessels, S. F. W. Neggers, L. J. Kappelle, C. J. M. Frijns, and A. Postma, "Brain areas involved in spatial working memory," *Neuropsychologia*, vol. 44, no. 7, pp. 1185–1194, Jan. 2006, doi: 10.1016/j.neuropsychologia.2005.10.005.

[9] T. Iachini, G. Ruggiero, M. Conson, and L. Trojano, "Lateralization of egocentric and allocentric spatial processing after parietal brain lesions," *Brain Cognition*, vol. 69, no. 3, pp. 514–520, Apr. 2009, doi: 10.1016/j.bandc.2008.11.001.

[10] M. Chechlacz, P. Rotshtein, and G. W. Humphreys, "Neuronal substrates of corsi block span: Lesion symptom mapping analyses in relation to attentional competition and spatial bias," *Neuropsychologia*, vol. 64, pp. 240–251, Nov. 2014, doi: 10.1016/j.neuropsychologia.2014.09.038.

[11] L. Piccardi, G. Iaria, F. Bianchini, L. Zompanti, and C. Guariglia, "Dissociated deficits of visuo-spatial memory in near space and navigational space: Evidence from brain-damaged patients and healthy older participants," *Aging, Neuropsychol., Cognition*, vol. 18, no. 3, pp. 362–384, May 2011, doi: 10.1080/13825585.2011.560243.

[12] R. P. C. Kessels, M. J. E. van Zandvoort, A. Postma, L. J. Kappelle, and E. H. F. de Haan, "The corsi block-tapping task: Standardization and normative data," *Appl. Neuropsychol.*, vol. 7, no. 4, pp. 252–258, Dec. 2000, doi: 10.1207/S15324826AN0704_8.

[13] K. Farrell Pagulayan, R. M. Busch, K. L. Medina, J. A. Bartok, and R. Krikorian, "Developmental normative data for the corsi block-tapping task," *J. Clin. Experim. Neuropsychol.*, vol. 28, no. 6, pp. 1043–1052, Sep. 2006, doi: 10.1080/13803390500350977.

[14] R. Brunetti, C. Del Gatto, and F. Delogu, "ECorsi: Implementation and testing of the corsi block-tapping task for digital tablets," *Frontiers Psychol.*, vol. 5, pp. 939–946, Sep. 2014, doi: 10.3389/fpsyg.2014.00939.

[15] M. H. G. Claessen, I. J. M. van der Ham, and M. J. E. van Zandvoort, "Computerization of the standard corsi block-tapping task affects its underlying cognitive concepts: A pilot study," *Appl. Neuropsychol., Adult*, vol. 22, no. 3, pp. 180–188, Sep. 2014, doi: 10.1080/23279095.2014.892488.

[16] A. Orsini, "Corsi's block-tapping test: Standardization and concurrent validity with WISC—R for children aged 11 to 16," *Perceptual Motor Skills*, vol. 79, no. 3, pp. 1547–1554, Dec. 1994, doi: 10.2466/pms.1994.79.3f.1547.

[17] A. Perrochon, G. Kemoun, B. Dugué, and A. Berthoz, ''Cognitive impairment assessment through visuospatial memory can be performed with a modified walking Corsi test using the 'magic carpet,''' *Dementia Geriatric Cognit. Disorders Extra*, vol. 4, no. 1, pp. 1–13, 2014, doi: 10.1159/000356727.

[18] H. Lee, G. Han, I. Lee, S. Yim, K. Hong, H. Lee, and S. Choi, ''Haptic assistance for memorization of 2-D selection sequences,'' *IEEE Trans. Human-Mach. Syst.*, vol. 43, no. 6, pp. 643–649, Nov. 2013, doi: 10.1109/TSMC.2013.2283464.

[19] Y.-J. Wu, P. Tseng, H.-W. Huang, J.-F. Hu, C.-H. Juan, K.-S. Hsu, and C.-C. Lin, ''The facilitative effect of transcranial direct current stimulation on visuospatial working memory in patients with diabetic polyneuropathy: A pre–post sham-controlled study,'' *Frontiers Hum. Neurosci.*, vol. 10, pp. 479–489, Sep. 2016, doi: 10.3389/fnhum.2016.00479.

[20] C.-L. Lin, P.-C. Lai, P.-C. Lai, P.-S. Chen, and W.-L. Wu, ''Pixel circuit with parallel driving scheme for compensating luminance variation based on a-IGZO TFT for AMOLED displays,'' *J. Display Technol.*, vol. 12, no. 12, pp. 1681–1687, Dec. 2016, doi: 10.1109/JDT.2016.2616507.

[21] C.-L. Lin, P.-S. Chen, M.-H. Cheng, Y.-T. Liu, and F.-H. Chen, ''A three-transistor pixel circuit to compensate for threshold voltage variations of LTPS TFTs for AMOLED displays,'' *J. Display Technol.*, vol. 11, no. 2, pp. 146–148, Feb. 2015, doi: 10.1109/JDT.2014.2383434.

[22] C.-L. Lin, F.-H. Chen, C.-C. Hung, P.-S. Chen, M.-Y. Deng, C.-M. Lu, and T.-H. Huang, ''New a-IGZO pixel circuit composed of three transistors and one capacitor for use in high-speed-scan AMOLED displays,'' *J. Display Technol.*, vol. 11, no. 12, pp. 1031–1034, Dec. 2015, doi: 10.1109/JDT.2015.2494064.

[23] H. B. Mann and D. R. Whitney, ''On a test of whether one of two random variables is stochastically larger than the other,'' *Ann. Math. Statist.*, vol. 18, no. 1, pp. 50–60, Mar. 1947, doi: 10.1214/aoms/1177730491.

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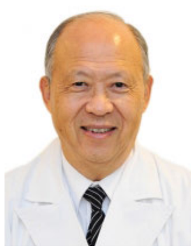

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