國立交通大學

電控工程研究所

博 士 論 文

全域或區域地標之虛擬環境中

尋路的學習行為與回憶時腦波活動

Learning Behavior and Retrieving EEG Activity of Wayfinding

in Virtual Environment with Global or Local Landmarks

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中 華 民 國 一 百 零 一 年 二 月

National Chiao Tung University

Institute of Electrical Control Engineering

Dissertation
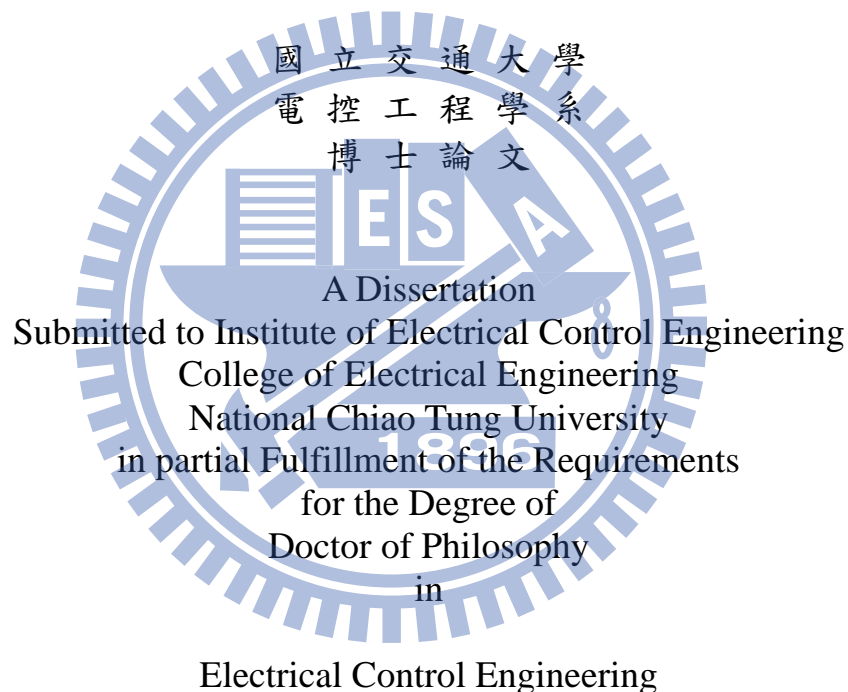
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電 控 工 程 學 系

博 士 論 文

A Dissertation
Submitted to Institute of Electrical Control Engineering
College of Electrical Engineering
National Chiao Tung University
in partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy
in

Electrical Control Engineering

February 2012

Hsinchu, Taiwan, Republic of China

中華民國一百零一年二月

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摘　　要

本研究建立一套用來研究人類空間巡行的可調式虛擬實境軟體，此軟體建構很多有用的功能，讓研究者可以設計虛擬空間巡行實驗以探討其行為表現與生理訊號。地標對於找尋目標是一個重要的參考位置，而很少有研究根據地標的特性:全域與區域地標，來探討對於空間巡行的影響，本研究建構只有全域地標或區域地標的虛擬環境，並且研究學習搜尋目標過程中性別的行為差異與使用學習後的記憶去搜尋目標過程中的腦波變化。在學習過程中，本研究使用全面的與深入的量測指標探討性別在規則迷宮中此兩種地標下搜尋目標的績效。全面性指標如校正距離與搜尋時間並沒有全部呈現出男生在空間巡行時的優勢，雖然女生搜尋時花了比較多的時間但是在距離上卻與男生無異。而深入性的指標提供了更多的資訊，女生遠離目標的時間比例較少，停在同一位置的時間比例較多且在不動時旋轉角度的比例較高，顯示出女生有可能先停止再藉由旋轉方向獲得更多的視覺資訊以進行下一步。簡而言之，男生在空間巡行時速度會比女生快，但不一定會比較有效率。

在使用已學習的記憶進行目標搜尋方面，本研究比較了在規則與不規則迷宮中以及全域與區域地標下的腦波 EEG 能量，並且有系統的將搜尋目標過程分為計劃、搜尋熟悉地點與跟隨腦內已知路徑的階段。額葉 theta 能量會上升如同文獻一樣，而在搜尋時到達最大之後在跟隨階段則會緩緩下降。在跟隨階段，額葉 beta 及後面腦區的 theta 同樣會有能量下降的現象顯示出心理活動的降低及警覺性的提高。而有較大視覺刺激範圍的全域地標比區域地標引發出更大額葉及枕葉的 delta 能量，不規則迷宮下誘發出較多枕葉 gamma 能量有可能是因為需要較多視覺訊號的處理。女生顯示出較小的額葉 theta 能量上升及較多的左邊感知運動區 gamma 能量下降，支持了女生仰賴更多地標資訊的觀點。

Learning Behavior and Retrieving EEG Activity of Wayfinding
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ABSTRACT

The current study introduced a software framework, FlexNavi (flexible navigation), for studying human navigation. FlexNavi provides many useful functions in virtual spatial navigation for researchers to design their idiosyncratic behavioral or neuroimaging experiments. Landmarks are important spatial information as the reference points for wayfinding. According to the characteristic of landmarks, current study built virtual environment with global or local landmarks, and investigated the gender behavior differences during learning to search targets, as well as analyzed EEG activities during retrieving spatial memory to search targets after learning. During learning, This study assesses gender differences in wayfinding in environments with global or local landmarks by analyzing both overall and fine-grained measures of performance. Both female and male participants were required to locate targets in grid-like virtual environments with local or global landmarks. Interestingly, the results of the two overall measures did not converge: although females spent more time than males in locating targets, both genders were generally equivalent in terms of corrected travel path. Fine-grained measures account for different aspects of wayfinding behavior and provide additional information that explains the divergence in overall measures; females spent less time traveling away from the target location, a higher proportion of time not traversing, and made more rotations when stopping than males did. Rather than unequivocally supporting male superiority in wayfinding tasks, both the overall and fine-grained measures partially indicate that males and females are differentially superior when using global and local landmark information, respectively. To summarize, males moved faster than females but did not necessarily navigate the spatial surroundings more efficiently. Each gender showed different strengths related to wayfinding; these differences require the application of both overall and fine-grained measures for accurate assessment.

During retrieving, this study investigated EEG power during two geometric structure mazes (regular and irregular) with global or local landmark types, and

systematically divided the navigation processes into planning, searching and cruising stages. The frontal theta power was increase during navigation as result of navigation literatures and reached maximum during searching stage then suppressed during cruising stage. During cruising stage, there were also frontal beta and posterior theta power suppression which would reflect the cognitive status change of mental activity and alertness. Global landmark with extensive stimulus field induced larger delta power of frontal and occipital cluster than local landmark. The larger gamma power of irregular structure may be due to the requisition of more visual processing. The result of female navigation demonstrated smaller increase of frontal theta power and larger decrease of left sensorimotor gamma power, and this would support the gender difference which females rely on more landmark information.

致　　謝

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Symbols

EEG : electroencephalograms

VE : virtual environment

VR : virtual reality

3D : three degree

WTK : WorldToolKit

TTL : transistor-transistor logic

P : corrected travel path

T : travel Duration

TR_{away} : ratio of duration for moving away from the target location to the total duration

$TR_{no\text{-}translation}$: ratio of duration without translation to the total duration

$ROT_{translation}$: rotation angle with translation

$ROT_{no\text{-}translation}$: rotation angle without translation

ANOVA : analysis of variance

ICA : independent component analysis

ERSP : Event-related Spectral Perturbation

I Introduction

Wayfinding refers to the purposive, directed, and motivated process of determining and following a route between an origin and a destination [1, cf. 2]. Further, finding one's route from current location to target location is involved with multiple brain processes. Numerous studies have investigated the cerebral activities related to wayfinding from depth electrodes [3-5], intracranial electroencephalograms [6-8], scalp electroencephalograms (EEG) [9-13], magnetic resonance imaging [14-27] and magnetoencephalography [28-29].

Wayfinding requires intricate interactions among multisensory perceptions of environmental and self-motion cues, spatial computations, executive processes, and various types of online and offline spatial representations [30]. Given the complex interactions among cues, representations, and computational processes, it is quite natural to observe differences in wayfinding between genders [10, 16, 31-34], age groups [14, 22-23, 35-36], experiment difficulties [6, 8, 19], performances [11, 26, 28], normal and unexpected events [18, 20, 29], cognitive status [3-5, 7, 9, 12-13, 17, 24-25, 27], and levels of expertise [15, 21, 37].

Among the factors that influence wayfinding abilities, gender has received the most attention from researchers because gender differences in wayfinding may be the most sizable of all differences in male and female cognitive abilities [38] and may have significant implications in pedagogy and environmental designs. Coluccia and Louse [39] reviewed experimental studies conducted between 1983 and 2003 that compared male and female performance in spatial orientation tasks. They found that 61 % of the wayfinding experiments showed that males performed better in wayfinding tasks, whereas the remaining experiments showed no gender difference. Coluccia and Louse [39] attributed the better performance of males in wayfinding to the males' larger visual short-term working memory (VSWM). This hypothesis predicts that the

emergence of gender differences in spatial orientation tasks depends on the difficulty, or load on VSWM, associated with different wayfinding tasks [however, 32, did not find interaction between gender and difficulty of task]. The prediction can be restated more generally: the environmental context may interact with the gender differences in cognitive capacity and lead to differential performance in wayfinding. Thus, determining how fundamental contextual characteristics interact with subject variables is crucial to understanding wayfinding.

One particularly essential contextual characteristic of wayfinding is the type of available landmarks. Landmarks are salient objects or geometric features in the environment that are not necessarily visual. However, given that human wayfinding relies primarily on visual cues, we confine the discussion to visual landmarks hereafter. Studies on insects, animals, and humans [e.g. 36, 40-42] have revealed that landmarks serve as reference points for both survey and route knowledge and assist in wayfinding performance [41, 43-45]. Landmarks can also help for building inner maps and doing decision making in mostly navigation tasks such as Morris water maze, T-junction maze, virtual taxi driving and virtual environments. Based on visuospatial characteristics, landmarks can be divided into two major categories: geometric landmarks and object landmarks. Geometric landmarks are structural or surface features in the environment [46], such as T-junction intersections, crossroads, arrangement of walls or boundaries of an area. Object landmarks, by contrast, are salient objects that can be easily distinguished from the background, such as the Eiffel Tower, a streetlamp, or a building with a peculiar exterior design. Regarding gender difference in processing landmarks, a previous study showed that whereas males could utilize both geometric and object landmarks, females relied primarily on object landmarks [47] in a virtual Morris water maze (MWM). This suggests that males may utilize different types of environmental features to find their way

more successfully.

Depending on the scale of visibility, object landmarks can also be divided into two other categories: global and local [48-51]. Global landmarks are visible everywhere inside the environment and can serve as references of absolute direction. Environment-wide visibility allows global landmarks to provide a stable frame of reference, which is particularly useful when traversing between two locations in separate occasions and along different routes [52-53]. By contrast, local landmarks can be observed only at limited locations and from restricted perspectives. The positional information provided by local landmarks can reduce errors in making turning decisions when learning the shortest route between two locations [45]. Given their distinct properties, global and local landmarks may facilitate the formulation of and access to cognitive maps in distinct ways.

Currently, only three studies have systematically analyzed the respective contributions of global and local landmarks to wayfinding, and none of these studies examined the interaction between landmark type and gender [49, 51, 54]. Steck and Mallot [51] asked participants to learn the spatial relationships between several places in a virtual city that had both global and local landmarks. After the learning phase, the spatial representations of participants were tested. Participants were asked to choose a direction at road intersections while landmarks were transposed or strategically misplaced. The results showed sizable variations among individuals. Participants' performance improved when either the local or the global landmark was available, as compared with a control condition without landmarks; this improvement suggests idiosyncratic reliance on global or local landmarks. Furthermore, Steck and Mallot (2000) also showed that people could perform highly when forced to use landmarks they were unaccustomed to using. This finding implies that individual differences may arise at the retrieving rather than at the encoding stage of spatial memory.

Hurlebaus et al. [49] asked participants to learn a path between two locations in a complex, cluttered, and unstructured virtual environment that contained both local and global landmark information. Participants were then asked to find their way in the same environment, with only global or local landmarks available. Some participants chose highly variable routes from trial to trial, whereas others were inclined to adopt fixed routes. The group exhibiting high variability in route choice showed dependence on global landmarks, whereas the group exhibiting fixed route choice relied on local landmarks. The differential dependence on global or local landmarks reflected the primary information each type of landmark carried: orientation information by global landmarks and positional information by local landmarks.

Ruddle et al. [54] asked participants to perform "out-and-back" navigation along a fixed route between two locations in a grid-structured environment (from A to B and then return to A). Participants were divided into four groups, each of which performed the navigation in one of four different environments: without landmarks, with global landmarks, with local landmarks, or with both global and local landmarks. These authors found that only local, not global, landmarks helped reduce errors in following the route. These authors attributed the lack of beneficial effects of global landmarks to participants' uncertainty in deciding where to make turns in an environment with orthogonal structures when only the global landmarks were available.

Both Steck and Mallot [51] and Hurlebaus et al. (2008) made both global and local landmarks available during the learning phases of their experiments; therefore, it was likely that participants constructed a cognitive map integrating both types of landmarks, which in turn allowed participants to rely on one type of landmark or the other as needed. Although global and local landmarks often coexist in daily life, presenting both simultaneously during the learning phase of an experiment makes evaluating their respective contributions to wayfinding

difficult; how participants would behave differently in environments with only global or local landmarks remains to be investigated. Other gaps in our understanding of wayfinding are also apparent. Ruddle et al.'s [54] findings that the presence of global landmarks produced no beneficial effect contradict previous findings and require clarification. Furthermore, after a review of the literature, we found no study that systematically compared gender differences in using global and local landmarks in online wayfinding. Given the lack of empirical investigation into how global or local landmarks independently contribute to wayfinding for each gender, experiments designed to explore this issue could advance the understanding of both the nature of gender differences and online wayfinding.

To this end, various studies have consistently indicated that males tend to pay more attention to global reference points and configurational aspects of the environment, whereas females focus on local features and procedural strategies such as how to get from one place to another [38, 55-57]. Recently, Coluccia et al. [58] tested male and female participants on map-drawing and a set of spatial orientation tasks to examine landmark, route, and survey knowledge. Consistent with earlier studies, Coluccia et al. (2007) found a strong relationship among various map-drawing skills and spatial orientation abilities, which were particularly more pronounced in males than in females. Because global landmarks could be easily used to determine environment-related orientation and local landmarks could be used as part of the detailed features inside the environment, it is reasonable to speculate that the gender difference revealed by the map-drawing study should be replicated in online wayfinding tasks involving global or local landmarks in a virtual environment (VE). Therefore, we hypothesize that the existence of a gender by landmark type interaction in the current study. In other words, males should perform higher than females in VEs with global rather than local landmarks, whereas females should perform as

well as or better than males in VEs with only local landmarks.

In the cerebral studies, no study has investigated the differences of EEG signals in the virtual environment with global or local landmarks based on our knowledge. And no study has systemically observed the dynamic activities of EEG during the processes of searching targets. To date, only one study has mentioned that frontal theta power difference virtual taxi driving. Weidemann et al. [13] revealed that theta activity in response to nontarget store views was larger than target store views during carrying passengers to defined store. This study hypothesized that theta power would increase until reaching a familiar location which participant can connect with target position in learned inner map then begin to decrease. In addition, navigation with global or local landmark would induce the different activities of EEG frequency band power.

The major aim of this study was to introduce a versatile software package, FlexNavi (meaning "FLEXible NAVIgation"), for creating virtual environment to test various wayfinding abilities. Then current study used FlexNavi to assess gender differences in online wayfinding in VEs with global *or* local landmarks. Specifically, global or local landmarks were placed on different blocks in the environments for the participants to use as references while they looked for targets. A variety of measurements were extracted from participants' travel paths to describe the metrics of task performance and physical behaviors [53]. Through the independent presentation of various types of landmarks and dependent measures that represent physical behaviors in the VE, this study illustrates both quantitative and qualitative differences in cognitive processing between females and males engaged in wayfinding in different environmental contexts. To investigate brain activities, current study also built two geometric structure mazes (regular and irregular) with two landmark types (global and local) respectively depending on landmark characteristic. The processes of searching targets were systematically divided into planning, searching and

cruising stages. Then this study analyzed time-frequency power and relative frequency band power (delta, theta, alpha, beta and gamma) of main clusters (frontal, central, left and right sensorimotor, parietal and occipital) between stages, geometric structures, landmark types and gender.

II Material

The virtual maze environment in the current study, FlexNavi, was implemented into two independent modules: the 3D environment module and the control module (Figure 1). The 3D environment module is a 3D model in 3ds-Max (Autodesk[®], San Rafael, CA, USA) compatible format (3ds format). The 3D model can be created with any 3D model software that can export 3ds format (e.g., Sketchup, Blender, Wings 3D and anim8or), and its layout is totally up to the research purpose of the users. The control module is implemented in Visual C++ using WorldToolKit (WTK) library (SENSE8[®]). The WTK library is an advanced cross-platform library for the development of high-performance and three-dimensional graphics applications. The C++ codes of the control module is compiled together with the WTK library functions into Windows executable file, which the user can run on IBM-compatible PC's with Windows XP, Vista, or Windows 7 installed.
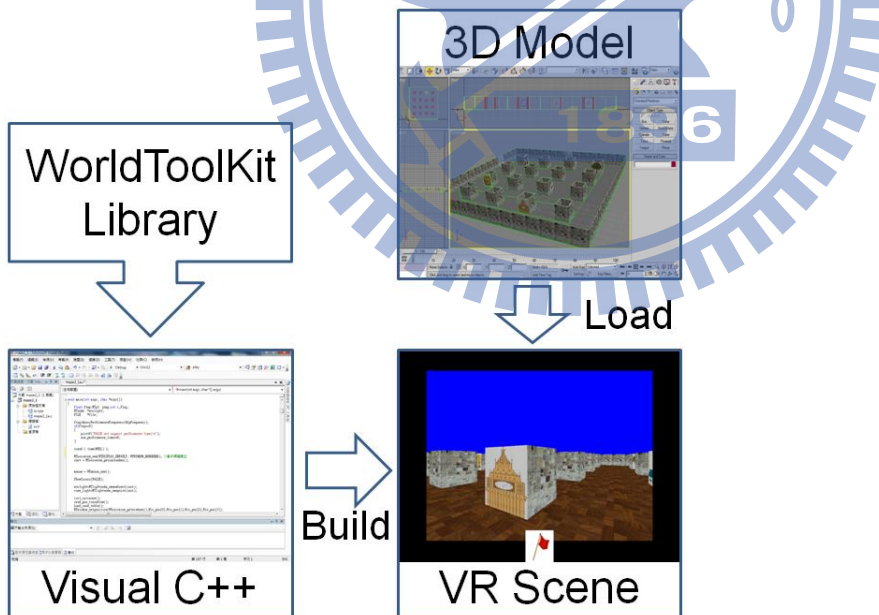
Figure 1.   Implementation flowchart of virtual maze

The control-module loads the 3D model and allows the user to navigate inside the virtual environment in the first-person view. This two-module

framework of implementation gives users the flexibility to create any kind of virtual environment layout that suits their research purpose, while avoiding the cumbersome process of acquiring programming skills. The configuration of the VR environment (Figure 2) and the features of events occurring in an experimental trial are specified in two text files. One of these "parameter" file stores the information regarding the path of the 3D models to be loaded in the experiment and various features of these models (coordinates and texture of starting point, goal location, and landmarks). The other file stores the behavior of the events, such as the sequence of different types of conditions, duration of a period, boundary of the goal location, type (keyboard, joystick, or mouse) and gain of the user's input, timing and port of TTL (transistor-transistor logic) trigger, … etc. The users can either directly edit these two parameter files to alter the appearance and behavior of the virtual environment, or edit them in a batch via any scripting language (e.g., MATLAB or python) when a few different configurations need to be altered quickly online. Full details of how to specify these parameters are as follows.
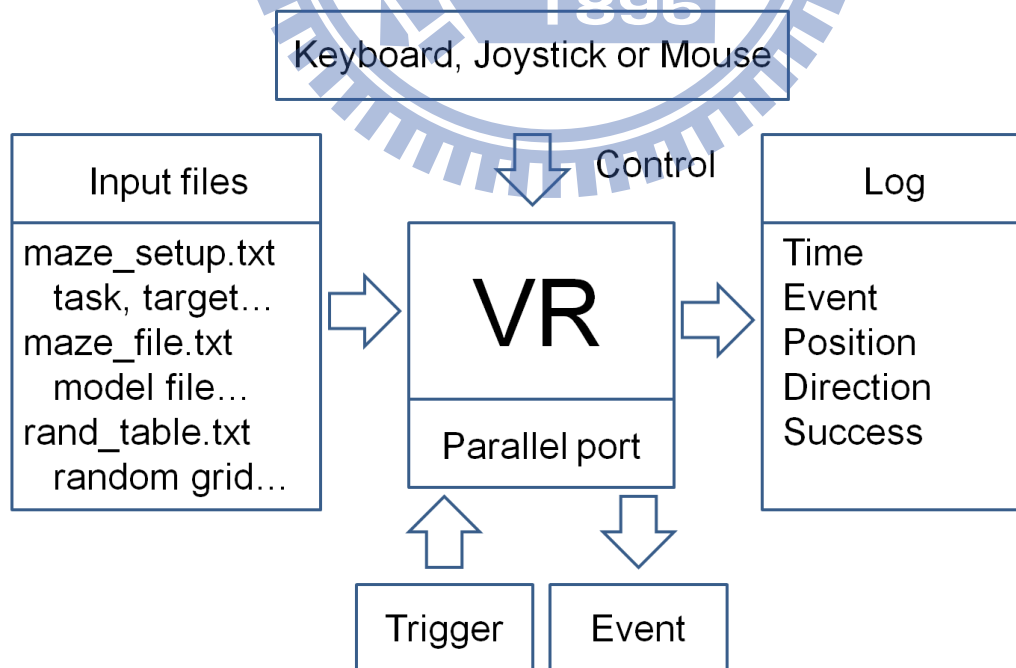
Figure 2.   The configuration of the VR environment

2.1. Usage

The FlexNavi has four main modes for user selection and combination. Except the searching task and navigation followed by defined sign, the other mode screen is halted at the last position.

2.1.1. Model 1: search targets

In Model 1 (Figure 3a), one target picture is shown on the bottom of screen and user should find the target within limiting time. User would be transferred to a random position before next searching task.

2.1.2. Model 2: motion condition

During the motion condition (Figure 3b), four white rectangles randomly display on the upper, bottom, left and right sides of screen then user must respond the correct direction by control keys.
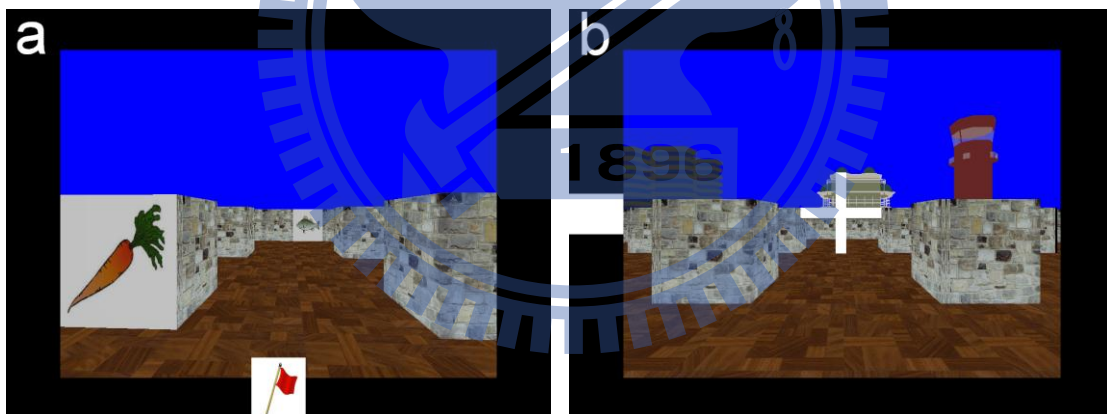
Figure 3.   (a) Search target. (b) Motion condition

2.1.3. Model 3: navigation followed by defined sign

In this mode (Figure 4a), user would navigate with defined sign which is loaded from the other 3ds file and is created without limit.

2.1.4. Model 4: static

In this mode, user can load one fixation marker and one picture to display in a full screen (jpeg and tga format). The black pixel of picture could be set

transparent (tga format only). In Figure 4b, the program will halt on current position with fixation marker. In Figure 4c, the program will transfer user to next start position and halt with fixation marker. In Figure 4d, the program will halt with fixation marker and current target picture.
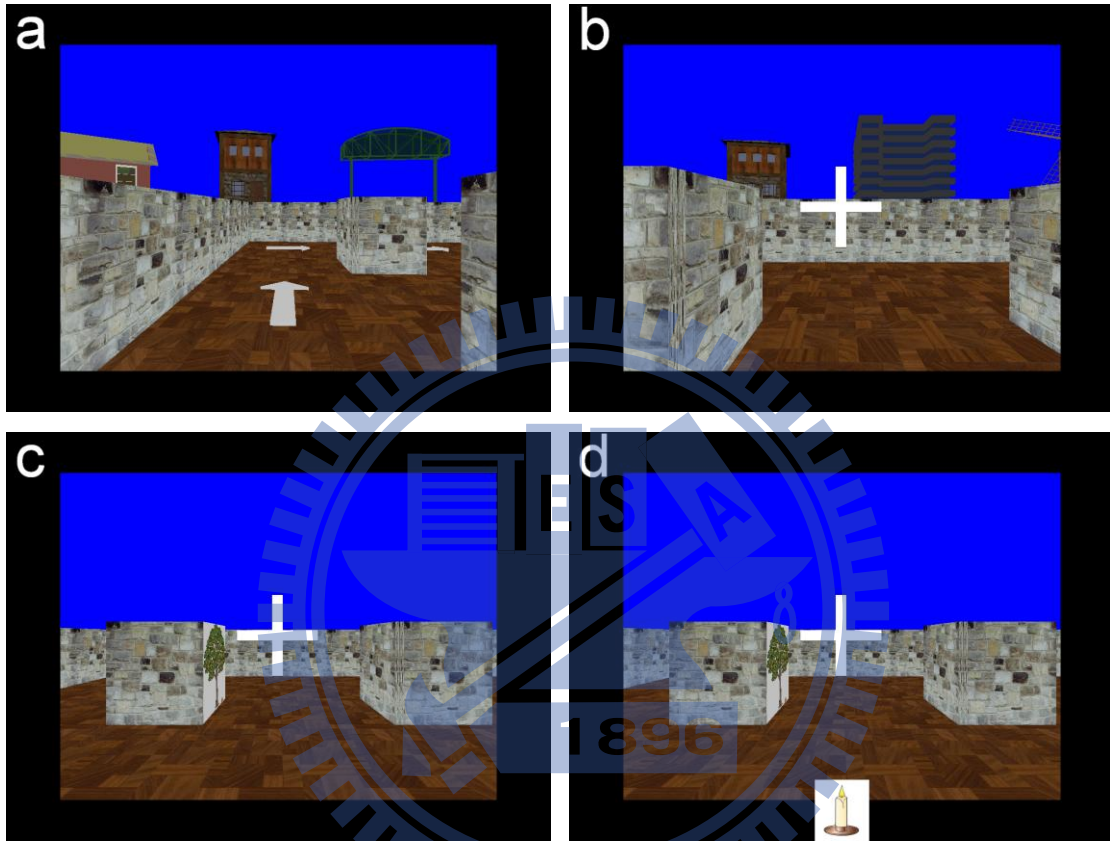
Figure 4.   (a) Navigation followed by defined sign. (b) Halt on current position with fixation marker. (c) Halt on transferred position with a fixation marker. (d) Halt with fixation marker and current target picture.

2.2. Input and output interface

User can use keyboard, joystick, and mouse to navigate. User can transmit 8 bits and receive one bit signal from parallel port. The output signal is event and grid position signal and the input signal is used to synchronize the tasks switch. The grid position is calculated by the position in the rectangular plane which is divided equally into several parts (Figure 5). The number of grid is

increased along with x axis from grid start point to end point. The program generates a log file after a user completed navigation. The file records information about landmark types, time, position, orientation, key pressed and whether user found the targets or not.

Grid end point

21	22	23	24	25
16	17	18	19	20
11	12	13	14	15
6	7	8	9	10
1	2	3	4	5

Grid start point

Figure 5.　　Schematic diagram of grid position.

2.3. Setup

There are three text files for user definition. The 'maze_setup.txt' includes the adjustable settings for basic environment and experiment procedure. The 'maze_file.txt' includes the list of 3ds models and pictures files. The 'rand_table.txt' includes the grid positions and directions of random start points.

2.3.1. 'maze_setup.txt'

In this file, the program allows the user to define various parameters, such as basic control, target environment, task mode, and input/output setups.

Basic control. The basic control setting includes the program window size, forward and rotational speed of navigation, pitch angle of viewpoint, the brightness of environment light, the log file name, the control keys, joystick and mouse.

Target environment. The target environment setting contain the total

numbers of mazes and targets, the number times of targets to find, the order of targets, whether showing the other target pictures during searching one target or not, the farthest distance between view position and target to display the target picture, the user-defended positions and directions for random start positions database of searching task, and the limited distances to make sure the available random start positions not too close to the end position of prior searching task and current target position.

Task mode settings. The task mode setup includes the order of task modes and durations, and the time to switch maze. The modes of task contain searching task, motion condition, navigation followed by defined sign, fixation marker in the center of screen, all black display, one full screen picture, and a center fixation marker with one picture background.

Input/output settings. The input/output setup includes the parallel port number, whether enabling the input or output port or not, and the pin number of input port (output port is fixed on pin 2 - 9).

2.3.2. 'maze_file.txt'

This file is the file name list of all models and pictures, it contains navigation environment, navigation start position, grid start position, grid end position, navigation guide (sign marker), targets models and targets pictures. The above positions are calculated by the center of loaded models which will be not displayed during navigation. The program supports the jpeg and tga format of pictures.

2.3.3. 'rand_table.txt'

This file includes the grid positions and directions of random start points. It must define the navigation environment number, target number and the numbers of random points of this target then define the grid positions and directions of these points.

Table 1. The guidelines of setup files

maze_setup.txt

lines	example	description
1	control_key=UP,DOWN,LEFT,RIGHT	Control keys (A~Z, 0~9, sign and arrow keys).
2	mouse_control_enable=0	Enable mouse control.
3	win_pos=0,0,1024,768,	Location and size of program window on screen (upper left x, upper left y, width, height).
4	maze_num=2	Numbers of navigation mazes.
5	elevation=0	Pitch angle of viewpoint during navigation.
6	corner=1	Turning angular velocity per frame.
7	viewangle=50	Horizontal view angle.
8	speed=1	Movement speed per frame.
9	filename=test.txt	Log file name.
10	target_num=3	Number kinds of targets.
11	show_dis=3000	The farthest distance between view position and target to display the target picture.
12	show_goal=0	Whether showing the current target after current task in this period or not.
13	search_num=4	Number times of seraching tasks.
14	search_order=0,2,1,2	Order of searching targets.
15	show_other_target=0	Whether showing the other targets pictures during searching one target or not.
16	find_target_dis=8	The farthest distance between view position and target to display the target picture.
17	collision_distance=1	The nearest distance between view position and models.
18	model_scale=1	The scale of loaded models.
19	envlight_intensity=0.75	Brightness of environment light (0 ~ 1).
20	viewlight_intensity=0.9	Brightness around view position (0 ~ 1).
21	viewlight_attenuation=0.1	Attenuation of point light from view position. The attenuation rate = 1 / (1+viewlight_attenuation*distance*distance).
22	print_port=888	Parallel port number (decimalism).
23	printport_in=0	Enable the input function from parallel port (one pin).
24	printport_out=0	Enable the output function from parallel port (pin 2~9).
25	printport_input_pin=12	Pin number of input port (1 ~ 17, some system support only 10 ~13 and 15).
26	continuous_check_signal=0	The type to synchronize the task switch. 0) After reaching the task switch time, the program will be halted and receive signal until received signal is correct. 1) The program receive signal

	continuously and will switch the task immediately when receiving the correct signal.
27 signal_number=0	The wanted value of input signal (0 or 1).
28 square_latency_ms=2000	Display time (ms) limit of one square in motion condition.
29 square_display_type=1	Display type of square in motion condition after response. 0) showing next square immediately. 1) wating until reaching display time limit.
30 grid_X=20	Part numbers of grid in x axis
31 grid_Y=20	Part numbers of grid in y axis
32 task_num=20	Numbers of task.
33 task_order=2,3,7,8,0,3,7,8, 0,3,1,3,7,8,0,3,7,8,0,3	The order of task modes. 0) Searching. 1)　Motion condition. 2) Navigation followed by defined sign. 3)　Fixation marker in the center of screen. 4) All black display. 5) One full screen picture. 6) A center fixation marker with one picture background. 7) Halt on transferred position with fixation marker. 8) Halt with fixation marker and current target picture.
34 task_timems=2000,2000,2 000,2000,15000,2000,200 0,2000,15000,2000,5000,2 000,2000,2000,15000,200 0,2000,2000,15000,2000	The order of task durations (ms).
35 task2_show_target=0	Whether showing all targets pictures or not in navigation followed by defined sign.
36 maze_change_mode=1	Enable navigation maze switch mode.
37 maze_change_number=2	Numbers of mazes switch.
38 maze_change_event_num ber=1,13	The time (task number) to switch maze.
39 maze_change_order=2,1	The order of mazes switch.
40 find_target_delay_ms=0,0	The delay time (ms) after finding targets (fix delay time, variable time). Delay time = fix delay time + 0 ~ variable time.
41 find_all_target_then_end= 1	Whether finishing this period or not after finding all targets.
42 find_target_then_next_bloc k=1	Whether switching the task to next one or not after finding one target.
43 rand_pos_enable=1	Enable random start position.
44 rand_pos_number=5	Numbers of random start positions database.
45 rand_pos=22,38,398,382,2 10	Grid positions (maze 1) for random start points database of searching task.
46 rand_dir=-1,-1,1,-1,1,1,-1,1	Directions (maze 1, x and z components of forward direction)

	,0,1	for random start points database of searching task.
47	rand_pos=22,38,398,382,2 10	Grid positions (maze 2) for random start points database of searching task.
48	rand_dir=-1,-1,1,-1,1,1,-1,1 ,0,1 …	Directions (maze 2) for random start points database of searching task.
	rand_dir=…	Directions (maze n).
49	rand_pos_start_not_range =50	The limited distance to make sure the available random start positions not too close to the end position of prior searching task.
50	rand_pos_goal_not_range =50	The limited distance to make sure the available random start positions not too close to the current target position.
51	fullscreen_picture=b.jpg	File name of one full screen picture task.
52	always_rand_pos=1	The type of random start position. 0) Transfer to random position after finding prior target. 1) Always transfer to random position before searching task.
53	rand_pos_order_enable=1	Enable transfering to fix start position each seaching task.
54	rand_pos_order=3,1,0,3	The order of fix transferred start position (the number of defineded random positions in the 'rand_table.txt').

maze_file.txt

lines	example	description
1	MAZE=maze1.3DS	File name of navigation environment (maze 1).
2	MAZE_POS=maze1_start1.3DS	File name of navigation start position (maze 1).
3	Grid_start=grid_start.3ds	File name of grid start position (maze 1).
4	Grid_end=grid_end.3ds	File name of grid end position (maze 1).
5	MAZE_guide=guide.3DS	File name of navigation guide (sign marker, maze 1).
6	MAZE=maze2.3DS	File name of navigation environment (maze 2).
7	MAZE_POS=maze2_start1.3DS	File name of navigation start position (maze 2).
8	Grid_start=grid_start.3ds	File name of grid start position (maze 2).
9	Grid_end=grid_end.3ds	File name of grid end position (maze 2).
10	MAZE_guide=guide.3DS	File name of navigation guide (sign marker, maze 2).
	…	…
	MAZE_guide=…	File name of navigation guide (maze n).
11	PICTURE_POS=target1_1.3DS	File name of target 1 model in maze 1.
12	PICTURE=t1_1.JPG	File name of target 1 picture in maze 1.
13	PICTURE_POS=target1_2.3DS	File name of target 2 model in maze 1.

14	PICTURE=t1_2.JPG	File name of target 2 picture in maze 1.
15	PICTURE_POS=target1_3.3DS	File name of target 3 model in maze 1.
16	PICTURE=t1_3.JPG	File name of target 3 picture in maze 1.
17	PICTURE_POS=target2_1.3DS	File name of target 1 model in maze 2.
18	PICTURE=t2_1.JPG	File name of target 1 picture in maze 2.
19	PICTURE_POS=target2_2.3DS	File name of target 2 model in maze 2.
20	PICTURE=t2_2.JPG	File name of target 2 picture in maze 2.
21	PICTURE_POS=target2_3.3DS	File name of target 3 model in maze 2.
22	PICTURE=t2_3.JPG	File name of target 3 picture in maze 2.
…	…	…
	PICTURE=…	File name of target m picture in maze n.

rand_table.txt

lines	example			description
1	maze	0		maze number
2	target	0	3	target number and the number of random points at this target
3		350	0	1 position and direction of first random point
4		303	-1	0 position and direction of second random point
5		246	0	1 …
6	target	1	2	the other target and random points number
7		100	0	-1
8		105	-1	0
9	target	2	4	
10		259	0	-1
11		378	1	0
12		195	0	-1
13		110	0	-1
14	maze	1		the other maze
15	target	0	4	
16		22	0	-1
17		38	1	0
18		398	0	1
19		382	-1	0
20	target	1	4	
21		22	0	-1
22		38	1	0
23		398	0	1
24		382	-1	0
25	target	2	5	

26	22	0	-1
27	38	1	0
28	398	0	1
29	382	-1	0
30	210	0	1

2.4. Log file

Log file records information about landmark types, time, position, orientation, key pressed and whether user found the targets or not.

Table 2. The description of log file

	log file
column	description
1	maze number
2	time
3	position x
4	position y
5	position z
6	direction x
7	direction y
8	direction z
9	target number
10	button status (0. none. 1. up. 2. down. 4. left. 8. right. 5. 1+4 up and left. ... etc.)
11	input signal of parallel port
12	output signal of parallel port (-1. none. 1~200. grid position. 201. search target. 202. motion condition. 203. navigation followed by defined sign. 204. fixation. 205. black screen. 206. fixation with picture. 207. picture. 208. fixation on next random position. 209. fixation with target picture. 210. finding target. 211~214. directions of motion condition. 215. correctly answer to motion condition)
13	task mode. (0. search target. 1. motion condition. 2. navigation followed by defined sign. 3. fixation. 4. black screen. 5. fixation with picture. 6. picture. 7. fixation on next random position. 8. fixation with target picture.)
14	find target or not.
15	direction of motion condition. (1. top. 2. bottom. 3. left. 4. right.)
16	correctly answer to motion condition
17	grid position

2.5. Examples

There are screen shots and setup files of two examples.

2.5.1. Example 1

Figure 6 shows the screen shots of example 1. In this example, user will search 4 targets in 6 minutes. The program loads 'ready.jpg' for initial display and halt until pressing the 'enter' button.

Figure 6.   Example 1.

Table 3. Setup of example 1

maze_setup.txt

lines	example	description
1	control_key=UP,DOWN,LEFT,RIGHT	Control keys are arrow keys
2	mouse_control_enable=0	Disable mouse control.
3	win_pos=0,0,1024,768,	Windows size from (0, 0) to (1024, 768).
4	maze_num=1	Only one maze.
5	elevation=0	Looking straight ahead.
6	corner=1	Turning one angle per frame .
7	viewangle=50	Fifty angle of horizontal view.
8	speed=1	The movement speed is one unit per frame.
9	filename=log_ex1.txt	save to log_ex1.txt
10	target_num=3	Three kinds targets.
11	show_dis=3000	The farthest distance between view position and target to display the target picture is 3000 unit.
12	show_goal=0	The current target is not showed after current task in each period.
13	search_num=4	Four seraching tasks.
14	search_order=0,2,1,2	Order of searching targets.
15	show_other_target=0	The other targets pictures are not showed during searching one target.

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16 find_target_dis=8	The farthest distance between view position and target to display the target picture is 8 units.	
17 collision_distance=1	The nearest distance between view position and models is 8 units.	
18 model_scale=1	The scale of loaded models is one.	
19 envlight_intensity=0.75	Brightness of environment light is 0.75.	
20 viewlight_intensity=0.9	Brightness around view positionis 0.9.	
21 viewlight_attenuation=0.1	Attenuation of point light from view position is 0.1.	
22 print_port=888	Parallel port number is 888 (0x378).	
23 printport_in=0	Disnable the input function from parallel port.	
24 printport_out=0	Disnable the output function from parallel port.	
25 printport_input_pin=12	No function.	
26 continuous_check_signal=0	No function.	
27 signal_number=0	No function.	
28 square_latency_ms=2000	Display time limit of one square in motion condition is 2 seconds.	
29 square_display_type=1	The next square is displayed until reaching display time limit in motion condition.	
30 grid_X=20	Part numbers of grid in x axis is 20.	
31 grid_Y=20	Part numbers of grid in y axis is 20.	
32 task_num=1	Only one task.	
33 task_order=0	The only one task is searching.	
34 task_timems=360000	The task durations is 6 minutes.	
35 task2_show_target=0	All targets pictures is not showed during task 2.	
36 maze_change_mode=0	Disnable navigation maze switch mode.	
37 maze_change_number=0	No function.	
38 maze_change_event_number=0	No function.	
39 maze_change_order=0	No function.	
40 find_target_delay_ms=0,0	No delay time after finding targets.	
41 find_all_target_then_end=1	The trial will be finished after finding all targets.	
42 find_target_then_next_block=0	It will not switch the task to next one after finding one target.	
43 rand_pos_enable=0	Disnable random start position.	
44 rand_pos_number=5	No function.	
45 rand_pos=22,38,398,382,210	No function.	
46 rand_dir=-1,-1,1,-1,1,1,-1,1,0,1	No function.	
47 rand_pos_start_not_range=50	No function.	
48 rand_pos_goal_not_range=50	No function.	

49 fullscreen_picture=b.jpg	The File name of one full screen picture task is 'b.jpg'.
50 always_rand_pos=1	Always transfer to random position before searching task.
51 rand_pos_order_enable=0	Disnable transfering to fix start position each seaching task.
52 rand_pos_order=3,1,0,3	No function.

maze_file.txt

lines	example	lines	example
1	MAZE=maze1.3DS	7	PICTURE=t1_1.JPG
2	MAZE_POS=maze1_start1.3DS	8	PICTURE_POS=target1_2.3DS
3	Grid_start=grid_start.3ds	9	PICTURE=t1_2.JPG
4	Grid_end=grid_end.3ds	10	PICTURE_POS=target1_3.3DS
5	MAZE_guide=guide.3DS	11	PICTURE=t1_3.JPG
6	PICTURE_POS=target1_1.3DS		

2.5.2. Example 2

Figure 7 shows the screen shots of example 2. Each picture shows the task number (upper left) and task modes (lower right). In this example, user will navigate two kinds of environments and search 4 targets. User will navigate with defined sign (first task, mode 2) in each initial environment then halt 2 seconds (second task, mode 3). There is a motion condition (11th task, mode 1) between two environments. Before searching task (fifth and 15th tasks, mode 0), the program will transferred user to defined position and halt 2 seconds without target picture (third task, mode 7) then display target picture 2 seconds (fourth task, mode 8). After searching task, the program will halt on current position 2 seconds without target picture (sixth task, mode 3).
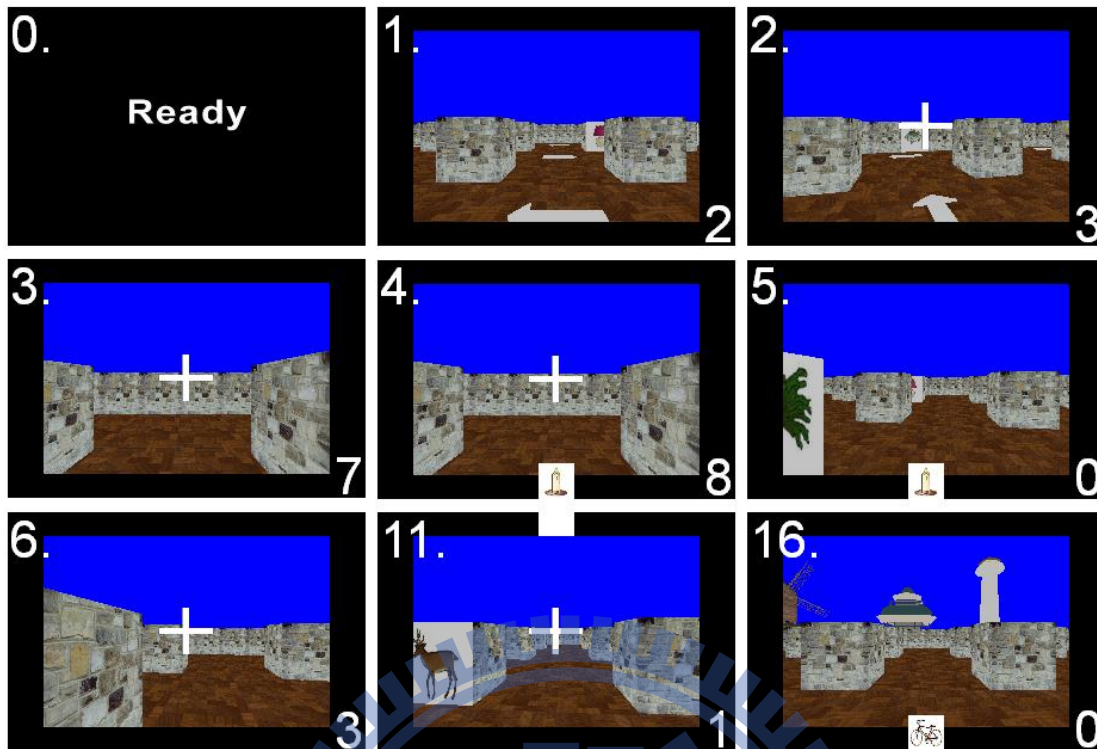
Figure 7.   Example 2.

Table 4. Setup of example 2

lines	Example	description
	maze_setup.txt	
1	control_key=W,S,A,D	Control keys are W, S, A and D.
2	mouse_control_enable=0	Disable mouse control.
3	win_pos=0,0,1024,768,	Windows size from (0, 0) to (1024, 768).
4	maze_num=2	Two kinds mazes.
5	elevation=0	Looking straight ahead.
6	corner=1	Turning one angle per frame .
7	viewangle=50	Fifty angle of horizontal view.
8	speed=1	The movement speed is one unit per frame.
9	filename=log_ex2.txt	save to log_ex1.txt
10	target_num=3	Three kinds targets.
11	show_dis=3000	The farthest distance between view position and target to display the target picture is 3000 unit.
12	show_goal=0	The current target is not showed after current task in each period.
13	search_num=4	Four seraching tasks.
14	search_order=0,2,1,2	Order of searching targets.
15	show_other_target=0	The other targets pictures are not showed during

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		searching one target.
16	find_target_dis=8	The farthest distance between view position and target to display the target picture is 8 units.
17	collision_distance=1	The nearest distance between view position and models is 8 units.
18	model_scale=1	The scale of loaded models is one.
19	envlight_intensity=0.75	Brightness of environment light is 0.75.
20	viewlight_intensity=0.9	Brightness around view positionis 0.9.
21	viewlight_attenuation=0.1	Attenuation of point light from view position is 0.1.
22	print_port=888	Parallel port number is 888 (0x378).
23	printport_in=0	Disnable the input function from parallel port.
24	printport_out=0	Disnable the output function from parallel port.
25	printport_input_pin=12	No function.
26	continuous_check_signal=0	No function.
27	signal_number=0	No function.
28	square_latency_ms=2000	Display time limit of one square in motion condition is 2 seconds.
29	square_display_type=1	The next square is displayed until reaching display time limit in motion condition.
30	grid_X=20	Part numbers of grid in x axis is 20.
31	grid_Y=20	Part numbers of grid in y axis is 20.
32	task_num=21	Twenty tasks.
33	task_order=2,3,7,8,0,3,7,8,0,3, 1,2,3,7,8,0,3,7,8,0,3	The order of task modes.
34	task_timems=2000,2000,2000, 2000,15000,2000,2000,2000,1 5000,2000,5000,2000,2000,20 00,2000,15000,2000,2000,200 0,15000,2000	The order of task durations (ms).
35	task2_show_target=0	All targets pictures is not showed during task 2.
36	maze_change_mode=1	Enable navigation maze switch mode.
37	maze_change_number=2	Mazes switchs two times.
38	maze_change_event_number= 1,12	The program will switch maze at task 1 and 12.
39	maze_change_order=2,1	The order of mazes switch.
40	find_target_delay_ms=0,0	No delay time after finding targets.
41	find_all_target_then_end=1	The trial will be finished after finding all targets.
42	find_target_then_next_block=1	It will switch the task to next one after finding one target.
43	rand_pos_enable=1	Enable random start position.

44	rand_pos_number=5	Five random start positions.
45	rand_pos=22,38,398,382,210	Grid positions for random start points database in first maze.
46	rand_dir=-1,-1,1,-1,1,1,-1,1,0,1	Directions for random start points database in first maze.
47	rand_pos=22,38,398,382,210	Grid positions for random start points database in second maze.
48	rand_dir=-1,-1,1,-1,1,1,-1,1,0,1	Directions for random start points database in second maze.
49	rand_pos_start_not_range=50	The limited distance to make sure the available random start positions not too close to the end position of prior searching task is fifty units.
50	rand_pos_goal_not_range=50	The limited distance to make sure the available random start positions not too close to the current target position is fifty units.
51	fullscreen_picture=b.jpg	The File name of one full screen picture task is 'b.jpg'.
52	always_rand_pos=1	Always transfer to random position before searching task.
53	rand_pos_order_enable=1	Enable transfering to fix start position each seaching task.
54	rand_pos_order=3,1,0,3	The order of fix transferred start position.

maze_file.txt

lines	example	lines	example
1	MAZE=maze1.3DS	12	PICTURE=t1_1.JPG
2	MAZE_POS=maze1_start1.3DS	13	PICTURE_POS=target1_2.3DS
3	Grid_start=grid_start.3ds	14	PICTURE=t1_2.JPG
4	Grid_end=grid_end.3ds	15	PICTURE_POS=target1_3.3DS
5	MAZE_guide=guide.3DS	16	PICTURE=t1_3.JPG
6	MAZE=maze2.3DS	17	PICTURE_POS=target2_1.3DS
7	MAZE_POS=maze2_start1.3DS	18	PICTURE=t2_1.JPG
8	Grid_start=grid_start.3ds	19	PICTURE_POS=target2_2.3DS
9	Grid_end=grid_end.3ds	20	PICTURE=t2_2.JPG
10	MAZE_guide=guide.3DS	21	PICTURE_POS=target2_3.3DS
11	PICTURE_POS=target1_1.3DS	22	PICTURE=t2_3.JPG

rand_table.txt

lines	example			lines	example			lines	example		
1	maze	0		15	195	0	-1	29	100	0	-1
2	target	0	4	16	110	0	-1	30	105	-1	0

#	label				#	label				#	label			
3		350	0	1	17	target	3	4		31		202	0	1
4		303	-1	0	18		179	0	1	32		30	-1	0
5		246	0	1	19		215	1	0	33	target	2	4	
6		286	-1	0	20		311	0	1	34		259	0	-1
7	target	1	4		21		362	1	0	35		378	1	0
8		100	0	-1	22	maze	1			36		195	0	-1
9		105	-1	0	23	target	0	4		37		110	0	-1
10		202	0	1	24		350	0	1	38	target	3	4	
11		30	-1	0	25		303	-1	0	39		179	0	1
12	target	2	4		26		246	0	1	40		215	1	0
13		259	0	-1	27		286	-1	0	41		311	0	1
14		378	1	0	28	target	1	4		42		362	1	0

III Methods

This study built two experiments based on the same program. Experiment 1 was designed for knowing the behavioral differences of gender during the learning processes of searching targets in the maze with global or local landmarks. Experiment 2 was established for observing the EEG phenomenon between searching stages, landmark types, geometric structures and gender during retrieving spatial memory to search targets after learning.

3.1. Experiment 1: learning behavior

3.1.1. Participants

Fifteen males (22.3±4.6 years) and fifteen females (20.5±3.5 years) from National Chiao-Tung University, Taiwan, participated in the experiment after providing informed consent. The participants were college students, were not personally related to the authors, had normal or corrected-to-normal vision, and did not exhibit any neurological or psychological pathology. Twelve males and six females reported that they played video games frequently on a questionnaire asking for their demographic information (that is, "Do you play computer games frequently?"). Participants received monetary compensation of NT$200 (approximately US$6.50) for their time.

3.1.2. Apparatus and materials

The virtual maze environment was implemented with a custom software system that displayed 3D environments and allowed users to navigate using a first-person view. The field-of-view (FOV) of the VE was approximately 37 degrees. The participants used four arrow keys on a QWERTY keyboard to move forward, backward, left, and right inside the maze. The layout of the maze included a 5×5 grid of interweaving roads and cubic blocks surrounded by walls (Figure 8a).

Figure 8.　　(a) A bird's eye view of the simple maze structure adopted in the current study; (b) first-person view of the global-landmark condition; (c) first-person view of the local-landmark condition.

　　To examine whether global (Figure 8b) and local (Figure 8c) landmarks lead to differential performance, we constructed two types of mazes. In the environment with global landmarks, eleven enormous structures (for example, a tower, lighthouse, water tower, windmill, and other buildings, Figure 9), which participants could see from everywhere inside the maze, were placed outside the surrounding walls. In the environment with local landmarks, eleven different cartoon pictures (an axe, banana, bell, bird, bow, radish, deer, fish, desk lamp, scissors, and umbrella, Figure 10) were placed on the sides of the cubic blocks inside the maze. Each local landmark appeared on only one side of a given cube. Participants could see a particular local landmark only from a few restricted orientations at certain locations inside the maze. However, if a participant modified his/her view by rotating at any position, he/she would see at least one landmark. Either local or global landmarks were displayed in each trial.

　　Four targets (an airplane, bicycle, grape, and penguin under the global landmark condition; and a candle, duck, flag, and kettle under the local landmark condition) were placed at different locations under each type of landmark condition. Each target was displayed on one side of a block that formed the internal structure of the maze, or on one segment of the surrounding walls. An icon of the target picture (0.1 width × 0.15 length of the screen) was

shown at the bottom of the display before its location was found. Locations and the appearance of the targets differed between the global and local landmark conditions.
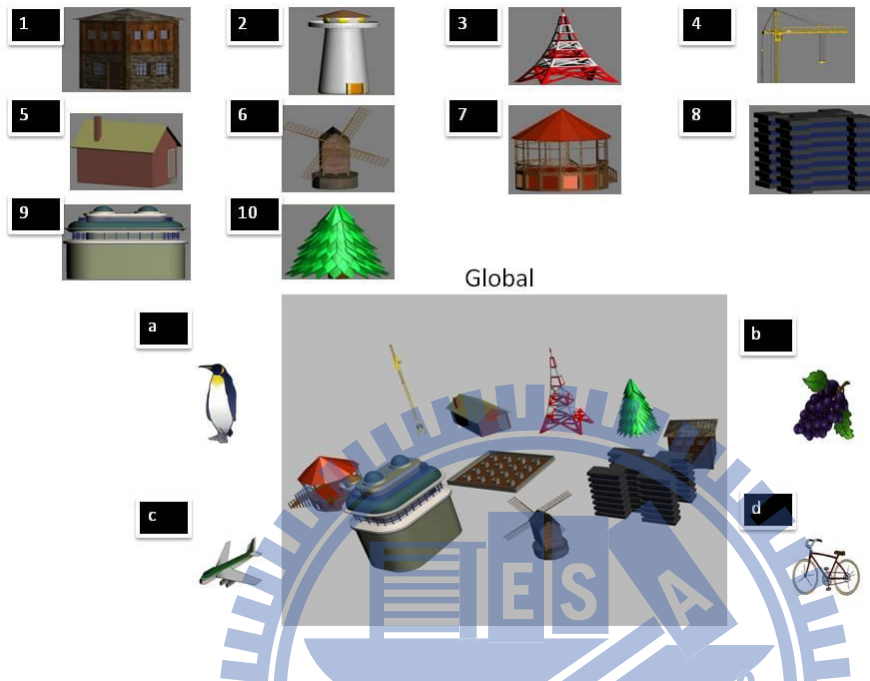
Figure 9.   Global landmarks and targets.

Figure 10.   Local landmarks and targets

3.1.3. Procedure

All participants were tested in both global and local landmark mazes: half of the participants were first tested with global landmarks, whereas the other half were first tested with local landmarks. Before the formal experiment started, the participants were briefed about the procedure and stimulus configuration, and they practiced using the arrow keys for controlling movement in the VE for approximately five minutes. The formal experiment involved eight trials under each landmark condition. Each trial started with a learning period in which participants could search for the targets until all were found or until a 6-minute period had elapsed. The learning period in each trial allowed participants to become familiar with the positions and spatial relationships among targets and landmarks. The testing period immediately followed the learning period, and the search time for each target location was limited to 20 seconds. Only one target was shown until it was found or until the 20-second time limit had elapsed. After finding a target, the participant's current view in the virtual environment was immediately transformed to another random location, and a new target picture appeared. During the testing period, each target appeared three times, giving a total of twelve target-searching periods. The testing period lasted until all targets were found or until the time limit (four minutes) was reached. The order of the targets in the learning and testing periods was randomized in each trial.

3.1.4. Dependent measures

Six dependent variables were involved in the wayfinding task:

1. The ratio of the actual travel distance divided by the optimal travel distance (corrected path, P);

2. The travel time between the beginning and the end of target searching (T);

3. The proportion of time when the participant was moving away from the target location (TR_{away});

4. The proportion of time when the participant was not traversing ($TR_{no-translation}$);

5. Accumulated angle of rotation when the participant was traversing ($ROT_{translation}$);

6. Accumulated angle of rotation when the participant was not moving ($ROT_{no-translation}$).

Although the corrected path and the overall travel time are regularly considered in wayfinding studies, the other dependent measures are rarely examined, and this study further investigates these measures to facilitate our understanding of wayfinding. Both TR_{away} and $TR_{no-translation}$ were ratios of their defining durations to the total travel duration. The duration of TR_{away} was calculated when the Euclidean distance between the current location and the target location at a given frame was increasing, as compared with the preceding frame. The duration of $TR_{no-translation}$ was calculated when the participant was not traversing (but could still be rotating at the same location) in the environment. By definition, TR_{away} and $TR_{no-translation}$ should develop in opposite directions. In the scenario of a small TR_{away} and a large $TR_{no-translation}$ during wayfinding, the participant may often stay in the same location to compare visual scenes carefully with mental representations of the environment in order to plan the optimal path. By contrast, in the scenario of a large TR_{away} and a small $TR_{no-translation}$, the participant may either get lost frequently or adopt an exploratory strategy of continuing to move in hopes of finding a recognizable landmark. The latter scenario naturally results in a larger P than does the former. $ROT_{translation}$ and $ROT_{no-translation}$ were derived by tallying the absolute values of the difference in heading orientation between successive frames when the participant was moving or not moving, respectively. A large $ROT_{translation}$ may result from frequent instances of unnecessary detours, and a large $ROT_{no-translation}$ may imply difficulty in determining the direction of the next move.

In the framework for levels of measurement metrics in wayfinding by Ruddle and Lessells [53], P and T were termed "performance measures", whereas TR_{away}, $TR_{no\text{-}translation}$, $ROT_{translation}$, and $ROT_{no\text{-}translation}$ were termed "physical behavior measures". Here, we refer to the former group as "overall measures" because they are indicative of the overall wayfinding performance, but they do not represent the minute (or "fine-grained") details of how participants find their way. We refer to the latter group of measures as "fine-grained measures" because each of these measures captures a structural aspect of wayfinding behavior, such as moving away from targets (TR_{away}), stopping ($TR_{no\text{-}translation}$), changing direction while moving ($ROT_{translation}$), and changing orientation while stopped ($ROT_{no\text{-}translation}$).

3.1.5. Data analyses

For each trial, twelve values, each representing one type of variable, were collected, and each participant completed eight trials in the global and local landmark conditions, respectively. The data from the first four trials and the data from the second four trials were averaged separately. All dependent variables from the thirty participants were subjected to a three-way mixed-design ANOVA, with gender as a between-subject factor and landmark type (global versus local) and trial blocks (the first and the second block) as within-subject factors. The significance level for all statistical comparisons was set at p-value < 0.05. Post hoc analysis was conducted with Tukey's HSD test.

3.2. Experiment 2: retrieving EEG

3.2.1. Participants

Eight males (25.3 ± 2.1 yrs) and eight females (20.5 ± 0.8 yrs) from National Chiao-Tung University, Taiwan, participated in the experiment after informed consent. All participants had normal or corrected-to-normal vision, and did not have any neurological/psychological pathology. Each participant received

monetary reward of 1700 NT$ (approximately 54.8 US$) for completing the experiment trials which last 3.5 hours in total.

3.2.2. Apparatus and materials

EEG signals were acquired from 62-channel Quik-Cap with two references at left and right mastoids by SynAmps2 amplifier (Compumedics Ltd., Australia). The electrode locations were based on the international 10-20 system. The contact impedance between electrode and scalp was less than 10 k-ohms.

The virtual maze environment was implemented with a custom software system that displayed 3D environments and allowed users to navigate in their first-person view. The participants used four arrow keys on the keyboard to move forward, backward, leftward, and rightward, respectively, inside the maze. The virtual environment varied in two dimensions: structural geometry: regular and irregular, and landmark types (global and local). Regarding structural geometry, the layout of the regular maze was a 5×5 grid of interleaving roads and cubic blocks surrounded by walls (Figure 11a - c). The irregular maze occupied the same area surrounded by walls as the regular one, but the internal structures and paths were constructed irregularly so that one cannot move from one end to the other without meeting making turns (Figure 11d - f). As for the landmark type dimension, the environment with global landmarks (Figure 11b, e) had eleven gigantic architectures (for example: tower, lighthouse, water tower, windmill, tree, house, office building and some different structure buildings) distributed outside the surrounding walls, which participants could see from everywhere inside the maze. In the environment with local landmarks (Figure 11c, f), ten different cartoon pictures (house, clock tower, torii, windmill, factory, another style of house, tree, Statue of Liberty, office building and bridge) were attached to the visible surfaces of the cubic blocks inside the maze. And each local landmark appeared on only one side of a given cube. Participants could see a particular local landmark only from a few restricted orientations at certain

locations. In addition, if a participant control his/her view by rotating at any position, they will see at least one landmark. Either local or global landmarks were displayed in any trial.
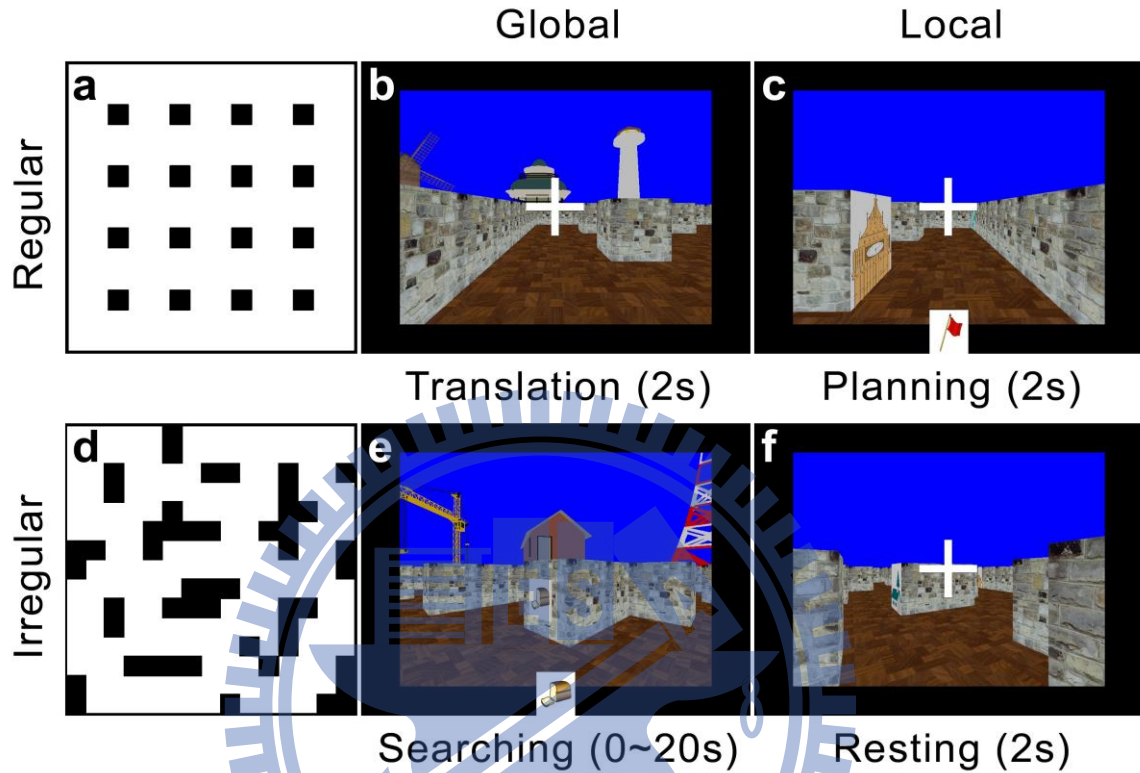
Figure 11.   (a) The bird's eye view of the regular maze structure adopted in the current study; (b) first-person view of the regular maze with global-landmark or (c) local-landmark condition; (d) The bird's eye view of the irregular maze structure; (e) first-person view of the irregular maze with global-landmark or (f) local-landmark condition. The procedure of experiment was translation (b), planning (c), searching (e) then resting (f) and the views of the above were the same condition during real experiment trials.

There were four targets (airplane, bicycle, grape and penguin for regular maze with global landmark; candle, duck, flag and kettle for regular maze with local landmark; toast, telephone, sweet corn and heart for irregular maze with global landmark; strawberry, guitar, lobster and scissors for irregular maze with

local landmark) located in different locations in each type of landmark condition. Each target was displayed on one side of the blocks which formed the internal structure of the maze, or on one segment of the surrounding walls (Figure 11e). An icon of the target picture (0.1 width × 0.15 length of the screen) was shown at the bottom of the display before the participant found its location. Locations and the outlook of the targets differed between the global and local landmark conditions.

3.2.3. Procedure

Data collection on each single participant took four days to complete. On the first two days, the participant was trained on one type of structure with either global or local landmarks, respectively, on the first day and then tested on the second day when EEG signals were also collected. Likewise, on the other two days the participant was trained and tested on the other type of structure with either type of landmark. Note that only those who performed well on the learning days (criteria described below) would proceed to the rest of the experiment.

On the first and third day, participants performed learning trials which alternated between studying and testing periods in each landmark condition until they could find all targets for two consecutive trials. Each trial started with a learning period when participants could navigate around the virtual environment and looked for targets until all were found or until they used up a 6-minute period. The learning period allowed participants to get familiar with the positions and spatial relationships among targets and landmarks. A testing period immediately followed the learning period where the searching time for each target location was limited to 20 seconds. Only one target was shown until it was found or the 20-second time limit was due. After finding a target, the current view in the virtual environment was immediately swapped to another random location and a new target picture appeared. During the testing period, each target

appeared two times, which totaled eight times of target searching. The orders of the target presence in the learning and testing periods were randomized, respectively, in every trial.

On the second and fourth day, participants performed ten testing trials. Each trial consisted of a set of eight target-searching periods in global landmark and another set of eight periods in local landmark. The order of landmark types in consecutive trials was reversed to counterbalance the serial order effect. An additional free walking period was included in current landmark condition at the beginning of a target-searching period and before the switch of landmark type for participants to adapt to the changes of visual scenes. The procedure of each target-searching period was similar to the testing period on the learning days and was separated into four steps: translation (Figure 11b), planning (Figure 11c), searching (Figure 11e) and resting (Figure 11f). At the beginning of a target-searching period, participants were instantly translated to random location where they stayed still and were asked to think where themselves were in the virtual environment for 2 sec. After the translation stage, a target picture appeared for a 2-sec planning stage when participants were required to think where the target was. Afterwards they were free to move and search the target during a maximal 20-sec period. Finally, either immediately after they arrived at the target location or until the time limit was due, participants rested for 2 sec, and then the next target-searching period began.

3.2.4. EEG Analyses

Signal Preprocessing, Component Selection, and Component Clustering

EEG data were preprocessed with a high-pass filter of 0.5 Hz and a low-pass filter of 50 Hz, and were then down-sampled to 250 Hz from 500 Hz. After visual inspection for removal of bad channels and artifacts, these signals were decomposed into independent sources in the brain by independent

component analysis (ICA) [59-60] using EEGLAB [39]. This resulted in 62 independent sources, or components, which were visually inspected and selected for further analysis in the following fashion: First, the residual variances of dipoles were screened and only those with less than 15% of residual variance were selected to ensure optimal fitting. Eye movement (the centers of scalp maps and dipole locations were around FP1 and FP2 channels) and muscle artifacts (the power spectra of component activations were larger between 30 Hz and 40 Hz than lower frequencies) were excluded from cluster analysis. Then, components with similar scalp maps (i.e., spatial distribution of energy), equivalent dipole locations and power spectra (i.e., with equivalent spatiotemporal profile of energy for each frequency band) from subjects were further grouped into the same clusters.

Segmentation of Events in Individual Epoch

For the selected clusters of components, EEG signals were segmented into 24 sec epochs from 1 sec prior to 23 sec following the starting time point of each target-searching period. The epochs of not finding the target before 21 sec from onset and the epochs without complete event signals (the signals were sometimes lost from experiment scene to amplifier) were excluded from the analysis. This resulted in 24% exclusion out of 3116 epochs. All included epochs consisted of the following events: random translation onset (0 sec), target onset (2 sec), searching onset (4 sec), arriving at the target location (4 - 21 sec), and final resting (2 sec following found target). Between searching onset and arriving at the target location, the participant's travelling path in each epoch was segmented into two different stages according to the characteristic of translation: 1) the searching stage which started from the beginning of translation until the beginning of following optimal route(s) leading to the target location; 2) cruising stage which started from to the beginning of moving along the optimal route(s) until arriving at the target position.

In the regular structure, the cruising stage began at the time point of the last local maximum of distances between target and all positions during searching. That is, during the cruising stage, the distance between the participants' momentary monotonically decreased until they found the target. In the irregular structure, we plotted all searching paths and then manually traced the optimal routes which led to target location without making detours (Figure 12). With the aforementioned events, five distinct stages were identified for each epoch: baseline, planning, searching, cruising and resting stages.
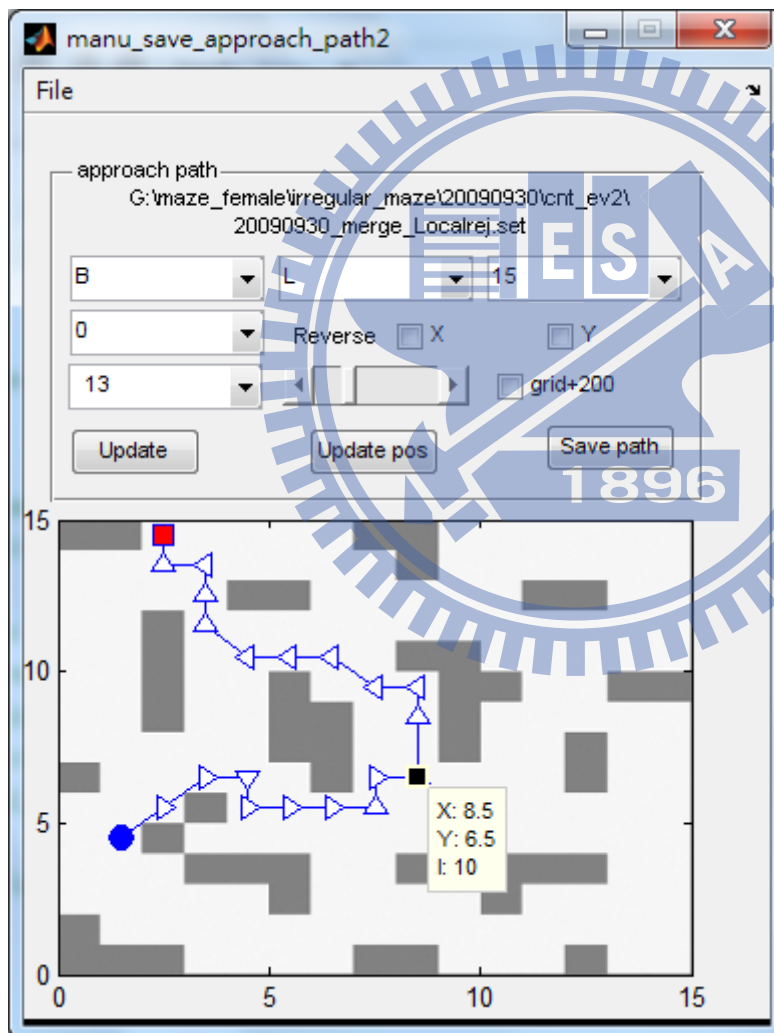
Figure 12.　Manual definition of the cruise onset.

Time-frequency analysis of Event-related Spectral Perturbation (ERSP)

ERSP was applied to all epochs to calculate the time-frequency power spectra of independent component activities. Because of variation of searching duration among epochs, the power spectra were aligned to the onset of the random translation event, searching stage, cruising stage and final resting stage in ERSP by applying the time-warp parameter in EEGLAB. The time-warp parameter could expand or contract specific time ranges of power spectra in each epoch by linearly transforming the frequency response onsets of all epochs to the same defined ranges. A time unit frequency response was calculated using a 256-point window with Hanning window then zero-padded to 1024 points. The power spectrum of the resultant data were then computed using a 1024-point fast Fourier transform.

Power spectra analyses were conducted to average the time-frequency power difference relative to the baseline power in time domain during planning, searching and cruising stages for every condition and in every participant. From each EEG component, twelve power spectra were extracted from the combinatory conditions of Wayfinding Stages (Planning, Searching, and Cruising), Landmarks Types (Global and Local), and Structural Geometry (Regular and Irregular).

Statistical analyses

Bootstrap resampling was utilized to assess the statistical significance of frequency power change of ERSP relative to the baseline power. The significance level was set at .001 (uncorrected for multiple comparisons).

Delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta1 (12-20 Hz), beta2 (20-28 Hz), gamma1 (28-35 Hz) and gamma2 (35-45 Hz) band power of clusters were respectively subject to a four-way mixed-design ANOVA, with Gender as a between-subject factor and Landmark Types (Global vs. Local), Structural Geometry (Regular vs. Irregular) and Wayfinding Stages (Planning,

Searching, and Cruising) as the within-subject factors. The significance level for ANOVAs was set at .05. Post hoc analysis was carried out with Student's t test, and familywise error rate was controlled with the Holm-Bonferroni correction [61]. Only significant effects were reported in the results section.

IV Results

Experiment 1 compared six behavioral variables between gender, landmark types and trial order. Experiment 2 grouped ICA components into six clusters and analyzed the ERSP of clusters. It also calculated the relative power spectra of frequency bands each participant then compares the power between gender, landmark types, geometric structures and searching stages.

4.1. Experiment 1: behavior results

4.1.1. Corrected travel path (P)

The three-way ANOVA revealed significant main effects of landmark type ($F(1, 28) = 56.94$, $p < .0001$, $\eta_p^2 = 0.67$) and trial blocks ($F(1, 28) = 32.43$, $p < .0001$, $\eta_p^2 = .54$) but not gender ($F(1, 28) = 0.85$, $p = .36$, $\eta_p^2 = .03$). The main effect of landmark type resulted from a longer P under the local (1.72) than under the global landmark (1.41) condition. The main effect of trial blocks resulted from a shorter P in the later trials (1.48) than in the earlier trials (1.65). Significant interactions were found between landmark type and trial blocks ($F(1, 28) = 4.30$, $p < .05$, $\eta_p^2 = .13$), and between landmark type and gender ($F(1, 28) = 5.04$, $p < .05$, $\eta_p^2 = .15$). The landmark type by trial blocks interaction was due to the larger difference between trials (1.83 for the first half vs. 1.61 for the second half of trials; $p < .01$) for the local landmarks than for the global landmarks (1.46 for the first half vs. 1.35 for the second half of trials; $p = .034$). The landmark type by gender interaction was due to the larger difference between global and local landmarks for males (1.39 vs. 1.80; $p < .0001$) than for females (1.42 vs. 1.64; $p = .003$). In addition, the difference between females and males did not significantly vary between landmark types (both ps > .05). The trial blocks by gender interaction ($F(1, 28) = 0.22$, $p = .64$, $\eta_p^2 = .01$) and the three-way interaction (($F(1, 28) = 3.46$, $p = .07$, $\eta_p^2 = .11$) did not reach significance.

A trend of three-way interaction was present but did not reach significance ($F(1, 28) = 3.46$, $p = .07$, $\eta_p^2 = .11$). As can be seen in Figure 13a, the difference in P between the first and second half of trials was larger for local than for global landmarks for males, but this difference did not occur for females. Consistent with this observation, we conducted two separate two-way ANOVAs with landmark type and trial blocks as the within-subject factors for each gender group and found a significant landmark type by trial blocks interaction in males ($F(1, 14) = 9.07$, $p < .001$, $\eta_p^2 = .39$) but not in females ($F(1, 14) = 0.02$, $p = .89$, $\eta_p^2 = .001$). The significant two-way interaction in males was due to the larger difference between the first half (1.93) and the second half of trials (1.67; $p < .001$) for the local landmarks than for the global landmarks (1.41 for the first half vs. 1.37 for the second half of trials; $p = .11$).

Because the starting position in each trial was randomly allocated, the average length of optimal paths may differ between conditions. If this is the case, it is likely that unequal lengths of corrected paths between groups or conditions were caused not only by experimental manipulations *per se* but also by the unequal lengths of optimal paths. To ensure that the results of corrected paths were not confounded by unequal lengths of optimal paths, the optimal path length was also subjected to the same ANOVA. Only the main effect of landmark type ($F(1, 28) = 83.65$, $p < .0001$, $\eta_p^2 = .75$) and the interaction between landmark types and gender ($F(1, 28) = 6.74$, $p < .05$, $\eta_p^2 = .19$) were significant. None of the other main effects (trial blocks: $F(1, 28) = 0.76$, $p > .39$, $\eta_p^2 = .02$; gender: $F(1, 28) = 0.38$, $p > .54$, $\eta_p^2 = .01$) or interactions (trial blocks by gender: $F(1, 28) = 0.44$, $p > .51$, $\eta_p^2 = .02$; landmark type by trial blocks: $F(1, 28) = 0.70$, $p > .41$, $\eta_p^2 = .03$; three-way interaction: $F(1, 28) = 0.11$, $p > .74$, $\eta_p^2 = .00$) reached significance. However, the pattern of results for optimal paths was quite distinct from those observed for corrected paths. First of all, the main effect showed that optimal path length under the global landmark condition (178)

was longer than optimal path length under the local landmark condition (162). Moreover, *post hoc* comparisons of the two-way interactions showed that although the optimal paths for females and males differed under the global landmark condition (175 for females vs. 181 for males, $p < .05$), the optimal paths for both genders did not differ significantly under the local landmark condition (164 for females vs. 160 for males, $p = .26$). This is exactly the opposite of the pattern observed in the results for corrected path length. In other words, although the optimal path length was shorter for the environment with local landmarks than with global landmarks, the participants actually traveled a longer distance in the former than in the latter. Thus, the results for the corrected path cannot be due to the unequal lengths of the optimal path.

4.1.2. Travel Duration (T)

The main effects of trial blocks ($F(1, 28) = 94.45$, $p < .0001$, $\eta_p^2 = .77$) and gender ($F(1, 28) = 19.13$, $p < .001$, $\eta_p^2 = .41$) were significant. As can be seen in Figure 13b, earlier trials took longer (10.00 seconds) to complete than later trials (8.64 seconds), and females took longer (10.27 seconds) on average than males (8.27 seconds). There was also a significant interaction between landmark type and gender ($F(1, 28) = 6.79$, $p < .05$, $\eta_p^2 = .20$). A post hoc analysis on the landmark type by gender interaction revealed that male participants spent similar amounts of time in both landmark environments (8.27 vs. 8.46 seconds for global and local landmarks, respectively; $p > .05$), whereas female participants spent less time finishing a trial under the local (9.78 seconds) than under the global condition (10.76 seconds; $p < .05$). In addition, males spent less time than females under both landmark conditions, and the difference between genders was larger in the global (2.52 seconds; $p = .0001$) than in the local (1.32 seconds; $p = .047$) condition. None of the other main effects (landmark type: $F(1, 28) = 3.13$, $p = .09$, $\eta_p^2 = .10$) or interactions (trial blocks by gender: $F(1, 28) = 0.87$, $p = .36$, $\eta_p^2 = .03$; landmark type by trial blocks: $F(1, 28) = 1.06$, $p = .31$, $\eta_p^2 = .04$;

three-way interaction: $F(1, 28) = 0.01$, $p = .93$, $\eta_p^2 = .00$) approached significance (see Figure 13b).
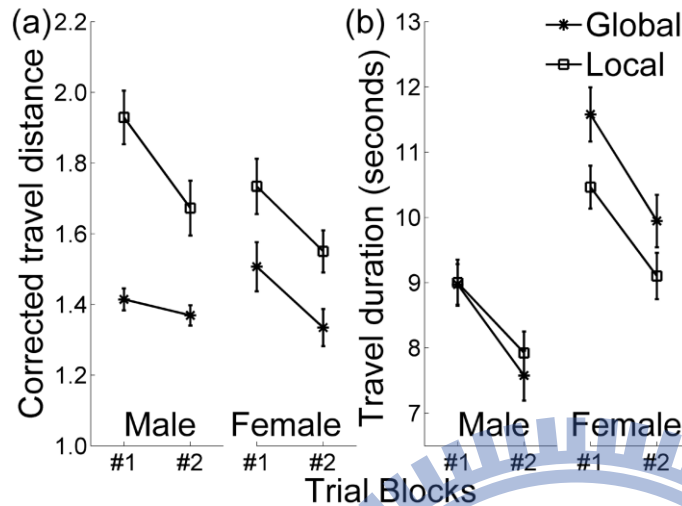
Figure 13. The corrected travel distance (a) and total travel duration (b) as a function of trial block, landmark types, and gender. Squares and asterisks indicate local and global landmarks, respectively. Error bars indicate standard error. The trial blocks were averaged separately for the first four trials (#1) and the second four trials (#2).

4.1.3. Ratio of duration for moving away from the target location to the total duration (TR_{away})

The main effects of landmark type ($F(1, 28) = 43.27$, $p < .001$, $\eta_p^2 = .61$), trial blocks ($F(1, 28) = 19.25$, $p < .001$, $\eta_p^2 = .41$), and gender ($F(1, 28) = 6.28$, $p < .05$, $\eta_p^2 = .18$) were significant. Figure 3a shows that in general, the proportion of time moving away from the target location was larger under the local (.057) than under the global (.033) landmark condition, larger in the earlier trials (.050) than in the later trials (.039), and larger for males (.052) than for females (.038).

Significant interactions were also found between landmark type and trial blocks ($F(1, 28) = 8.50$, $p < .01$, $\eta_p^2 = .23$). Post hoc analysis revealed that the difference in TR_{away} between the first and the second half of the trials was larger for the local landmarks (0.07 vs. 0.05; $p < .05$) than for the global landmarks

(0.04 vs. 0.03; $p = .22$). The landmark type by gender interaction was marginally significant ($F(1, 28) = 3.71$, $p = .06$, $\eta_p^2 = .12$). A post hoc comparison revealed that the difference between females and males was not significant in the global landmark condition (0.03 vs. 0.04; $p = .7$), but this difference was significant in the local landmark condition (0.05 vs. 0.07; $p = .014$). In addition, the difference between global and local landmarks was larger in males (0.04 vs. 0.07; $p < .001$) than in females (0.03 vs. 0.05; $p = .013$). The trial blocks by gender interaction was not significant ($F(1, 28) = 0.18$, $p = .67$, $\eta_p^2 = .01$).

The three-way interaction was also significant ($F(1, 28) = 6.83$, $p < .05$, $\eta_p^2 = .20$). As can be seen in Figure 14a, the difference in TR_{away} between the first and second half of the trials was larger for the local than for the global landmarks for males, whereas there was no difference for females. In accordance with this observation, separate follow-up tests for each gender revealed a significant interaction between landmark types and trial blocks ($F(1, 14) = 15.19$, $p < .01$, $\eta_p^2 = .52$) for males but not for females ($F(1, 14) = .05$, $p = .83$, $\eta_p^2 = .00$).

4.1.4. Ratio of duration without translation to the total duration ($TR_{no\text{-}translation}$)

The main effects of landmark ($F(1, 28) = 48.48$, $p < .0001$, $\eta_p^2 = .63$), trial block ($F(1, 28) = 8.58$, $p < .01$, $\eta_p^2 = .24$) and gender ($F(1, 28) = 31.66$, $p < .0001$, $\eta_p^2 = 0.53$) were significant. Figure 14b shows that in general, the proportion of time spent at the same location was longer under the global (0.66) than under the local (0.58) landmark condition, longer in the first half of trials (0.63) than in the second half of trials (0.61), and longer for females (0.67) than for males (0.57).

Significant interactions were also found between landmark types and trial blocks ($F(1, 28) = 7.03$, $p < .05$, $\eta_p^2 = .20$). Post hoc analysis revealed that the difference in $TR_{no\text{-}translation}$ between the first and the second half of trials was larger for the global landmarks (0.67 vs. 0.64; $p = .12$) than for the local

landmarks (0.58 vs. 0.58; p = .87). The three-way interaction ($F(1, 28)$ = 3.44, p = .07, η_p^2 = .11) and trial blocks by gender interaction ($F(1, 28)$ = 3.92, p = .06, η_p^2 = .12) were marginally significant. As can be seen from Figure 14b, the difference in $TR_{no\text{-}translation}$ between the first and second half of trials was larger for global than for local landmarks for males, whereas no difference was apparent for females. Consistent with this observation, separate follow-up tests for each gender revealed a significant interaction between landmark types and trial blocks ($F(1, 14)$ = 7.46, p < .05, η_p^2 = .35) for males but not for females ($F(1, 14)$ = .50, p = .49, η_p^2 = .03). The landmark type by gender interaction did not approach significance ($F(1, 28)$ = 0.21, p = .65, η_p^2 = .01).

Figure 14. TR_{away}(a) and $TR_{no\text{-}translation}$(b) as a function of trial block, landmark types, and gender. Squares and asterisks indicate local and global landmarks, respectively. Error bars indicate standard error. The trial blocks were averaged separately for the first four trials (#1) and the second four trials (#2).

4.1.5. Rotation angle with translation ($ROT_{translation}$)

The main effects of landmark type ($F(1, 28)$ = 12.54, p < .01, η_p^2 = 0.31) and gender ($F(1, 28)$ = 32.03, p < .0001, η_p^2 = 0.53) were significant. The angle of rotation during translation was larger under the local (72°) than under the global (56°) landmark condition and larger for males (95°) than for females (33°)

(Figure 15a). None of the other main effects (trial blocks: $F(1, 28) = 0.11$, $p = .74$, $\eta_p^2 = .00$) or interactions (landmark type by gender: $F(1, 28) = 1.57$, $p = .22$, $\eta_p^2 = .05$; trial blocks by gender: $F(1, 28) = 0.08$, $p = .78$, $\eta_p^2 = .00$; landmark type by trial blocks: $F(1, 28) = 2.55$, $p = .12$, $\eta_p^2 = .08$; three-way interaction: $F(1, 28) = 0.05$, $p = .82$, $\eta_p^2 = .00$) reached significance.

4.1.6. Rotation angle without translation ($ROT_{no\text{-}translation}$)

The main effects of landmark type ($F(1, 28) = 22.32$, $p < .0001$, $\eta_p^2 = .44$), trial order ($F(1, 28) = 70.68$, $p < .0001$, $\eta_p^2 = .72$) and gender ($F(1, 28) = 23.57$, $p < .0001$, $\eta_p^2 = .46$) were significant. The angle at which participants rotated at the same location was larger under the global (259°) than under the local (219°) landmark condition, larger in the first half of trials (261°) than in the second half of trials (217°), and larger for females (271°) than for males (207°) (Figure 15b).

The landmark type by gender interaction was marginally significant (landmark type by gender: $F(1, 28) = 3.29$, $p = .08$, $\eta_p^2 = .11$). Post hoc comparisons revealed that the difference between females and males was larger in the global landmark condition (299° vs. 210°, $p < .001$) than in the local landmark condition (244° vs. 195°, $p = .016$). In addition, the difference between global and local landmarks was larger in females ($p = .001$) than in males ($p = .19$).

There was also a significant interaction between landmark types and trial blocks ($F(1, 28) = 6.80$, $p < .05$, $\eta_p^2 = .20$). This interaction was due to the larger difference between the first and second half of trials for the global landmarks (288° vs. 230°; $p < .001$) than for the local landmarks (235° vs. 204°; $p = .02$). None of the other interactions approached significance (trial blocks by gender: $F(1, 28) = 0.25$, $p = .62$, $\eta_p^2 = .01$; three-way interaction: $F(1, 28) = 0.57$, $p = .46$, $\eta_p^2 = .02$).
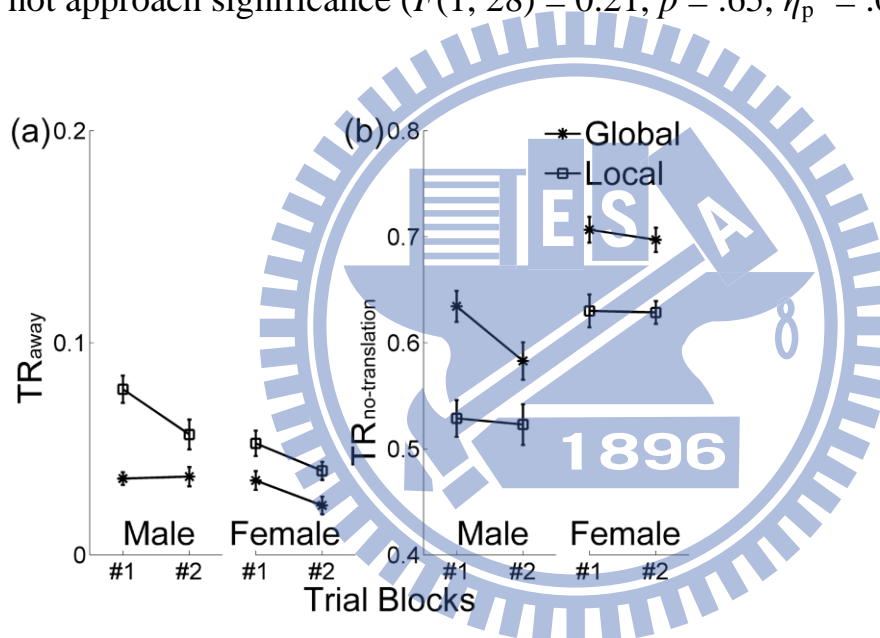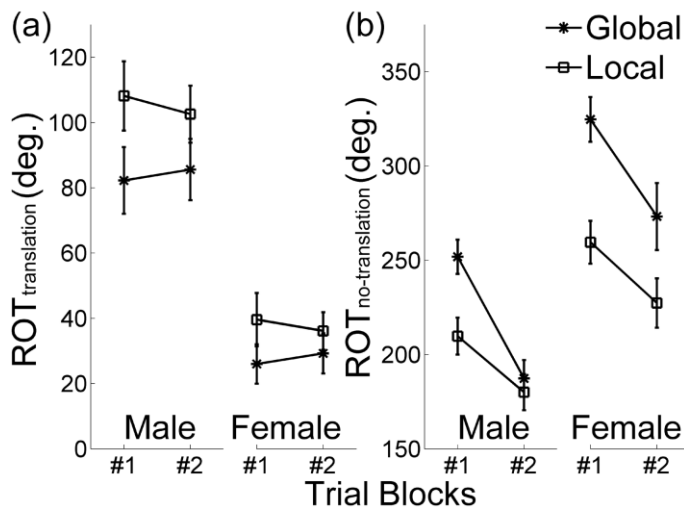
Figure 15. $ROT_{translation}$(a) and $ROT_{no\text{-}translation}$(b) as a function of trial block, landmark types, and gender. Squares and asterisks indicate local and global landmarks, respectively. Error bars indicate standard error. The trial blocks were averaged separately for the first four trials (#1) and the second four trials (#2).

4.2. Experiment 2: EEG results

4.2.1. Time-frequency Analysis of Independent Clusters

The components decomposed from EEG signals were grouped into six clusters: mid-frontal, central, left and right sensorimotor, parietal and occipital. The frontal ERSP revealed that the theta band power increased during the Planning stage, rose to its peak at the Searching stage, and then gradually returned to baseline during the Cruising stage (Figure 16). The other cluster of component ERSPs showed that power slightly (central) or visibly (left and right sensorimotor, parietal and occipital) suppressed around 10 Hz and 20 Hz (alpha blocking) between target onset and arriving at target then rebounded during resting.
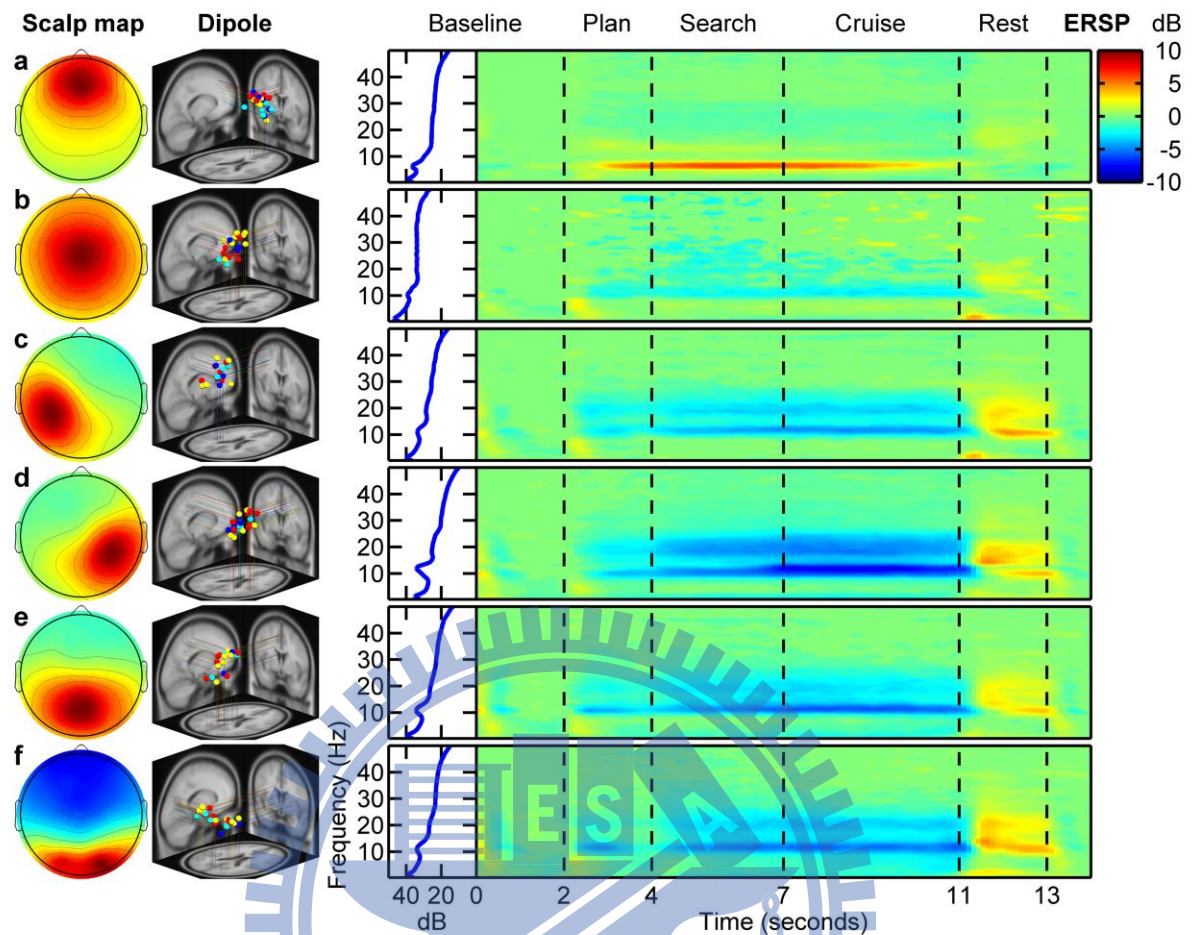
Figure 16.   This figure showed the scalp maps, dipoles locations and ERSPs of six grouped clusters: frontal (a), central (b), left (c) and right sensorimotor (d), parietal (e) and occipital (f). The areas between broken lines from left to right represent baseline (0~2 s), plan (2~4 s), search (4~7 s), cruise (7~11 s), and rest stages (11~13 s), respectively. The left curve is baseline spectra power and the center color map indicates frequency power difference related to baseline power. The frontal theta band power increased during the Planning stage and rose to the peak at search stage then slowly returned to baseline power during the Cruising stage. And the other components ERSPs showed alpha blocking (suppression) between target onset and arriving at target. The color of dipoles indicated different conditions: male in regular (blue) and irregular (sky blue) mazes and female in regular (red) and irregular (yellow) mazes.

4.2.2. Power Spectra Analyses

Participants whose data contained cluster components from ICA decomposition (frontal: 6 males and 7 females; central: 3 males and 7 females; left sensorimotor: 4 males and 5 females; right sensorimotor: 5 males and 7 females; parietal: 3 males and 5 females; occipital: 4 males and 7 females) were included in further statistical analyses. Therefore, forty two separate ANOVA were carried out on the combinations of frequency bands and clusters, respectively. These result were displayed on Table 5 (see Appendix 1 for detal interaction information) and grouped distributively in each condition as follows.

Table 5. Cluster frequency bands showing significant main effects are indicated with asterisks in the corresponding cell.

			Main effect					Description	
Code	Cluster	Band	Stage	Gender	Landmark	Structure	Interaction	Main	Posthoc
a4 c	Frontal	δ	**		*			p>s>c; g>l	
a1		θ	*					s>c>p	
		α							
a3		β1	**					p,s>c	
a3		β2	*				o		G p>c
		γ1							
		γ2							
c	Central	δ			*			g>l	
		θ							
a2		α	**				o		M p>c
a2		β1	*					p>s	
a2		β2	*				o		RG p>s,c; IG p>s
		γ1	*						
d		γ2					o		MP r>i
c	Left sensorimotor	δ					o		P g>l
		θ							
a2		α	**					p>s,c	
a2		β1	**					p>s,c	
a2		β2	**					p>s,c	
b		γ1		*				m>f	
		γ2							
a4 c	Right sensorimotor	δ	**				o		ML i>r; MR g>l; G p>c; L p>s,c
		θ							
a2		α	**				o		FLR p>s,c; FGR, FGI, FLI p>c
a2		β1	**				o		F p>s>c; M p>s,c
a2		β2	**				o		RG, RL, IG p>s; IL p>c
		γ1	*				o		F p>s,c
		γ2							
a4	Parietal	δ	*				o		F p>c
a2		θ	*					s>c	
a2		α	**					p,s>c	
a2		β1	**				o		G p>s,c; L p>c
a2		β2							
		γ1							
		γ2							
a4 c	Occipital	δ	*		*			p>s>c; g>l	
a2		θ	*					p>s>c	
a2		α	**					p>s>c	
a2		β1	**				o		F p>s,c; M p>s>c
a2		β2	**				o		FL p>c; FG, MG, ML p>s,c; RG, RL, IG, IL p>s,c
d		γ1	*				o		R p>s,c; I p,c>s; C i>r
		γ2							

*p<.05, **p<.001

o: There were interactions.

P: plan, S: search, C: cruise, G: global, L: local, F: female, M: male, R: regular and I: irregular.

These power differences were grouped into Stage (a1: frontal theta; a2: alpha and beta in the other clusters; a3: frontal beta; a4: delta in most clusters), Gender (b), Landmark (c) and Structure (d).

The capital letter meant the comparison was executed in this condition, and the lower case indicated the significant difference (p < .05) and relations between these conditions. Only significant differences were shown in the table.

4.2.3. Stage

The relative power of frontal in ERSP showed theta increase and its ANOVA results also revealed significant main effect of Stage in the frontal theta band ($F(2, 22) = 22.05$, $p < .001$, $\eta_p^2 = .67$) and no significant interactions between Stage and other factors (Table 5a1). The theta power (Figure 17a) of the Searching stage (3.24) was larger than that of the Cruising stage (2.22), which was in turn larger that the Planning stage (1.55).

The other cluster (except frontal) demonstrated the alpha blocking also revealed significant main effect of Stage in the alpha ($F(2, 14) = 34.72$, $p < .001$, $\eta_p^2 = 0.83$), beta1 ($F(2, 14) = 25.44$, $p < .001$, $\eta_p^2 = .78$) and beta2 band ($F(2, 14) = 43.74$, $p < .001$, $\eta_p^2 = .86$) in left sensorimotor (counter-lateral of control hand) and no significant interactions between Stage and other factors (Table 5a2). The alpha, beta1 and beta2 power of the Planning stage (-2.63, -2.55 and -1.92) were larger than that of the Searching (-3.54, -3.73 and -2.97) and Cruising stages (-3.87, -3.85 and -3.04), Furthermore, most alpha and beta power of Planning stage were also significant larger than that of the Searching or Cruising stages in central, right sensorimotor, parietal and occipital (Table 5a2). Although the

power difference between Stages not reached significant level in few conditions (female central alpha, male right sensorimotor alpha and parietal beta2), this also had similar trend revealed the largest alpha and beta power of the Planning stage. Moreover, the parietal and occipital theta power had the similar difference of stages with alpha power and revealed significant main effects of Stage in the theta band (parietal: $F(2, 12) = 8.60$, $p < .01$, $\eta_p^2 = .59$; occipital: $F(2, 18) = 34.83$, $p < .001$, $\eta_p^2 = .80$) and no significant interactions between Stage and other factors (Table 5a2). The parietal and occipital theta power of the Searching stage (-0.32 and -1.01) were larger than that of the Cruising stage (-0.94 and -2.02).

In the other obvious effect, there was a significant main effect of Stage in the frontal beta1 band ($F(2, 22) = 12.07$, $p < .001$, $\eta_p^2 = .52$) and no significant interactions between Stage and other factors (Table 5a3). The beta1 power (Figure 17a) of the Planning (0.28) and Searching stages (-0.01) were larger than that of the Cruising stage (-0.36), Further, there was also a significant main effect of Stage in the frontal beta2 band ($F(2, 22) = 7.66$, $p < .01$, $\eta_p^2 = .41$) and a significant interaction between Stage and Landmark ($F(2, 22) = 4.48$, $p < .05$, $\eta_p^2 = .29$). Post hoc analysis indicated the beta2 power of the Planning stage (-0.23) was significant larger than that of the Cruising stage (-0.61) in Global landmark and this power of the Planning stage (-0.47) was only showed a larger trend than that of Cruising stage (-0.60) in Local landmark.

Furthermore, the delta band power demonstrated differences between stages across some clusters (Table 5a4). There were significant main effects of Stage in the frontal ($F(2, 22) = 25.07$, $p < .001$, $\eta_p^2 = .70$) and occipital delta band ($F(2, 18) = 40.71$, $p < .001$, $\eta_p^2 = .82$) and no significant interactions between Stage and other factors. The frontal (Figure 17a) and occipital delta power of the Planning stage (0.48 and -0.25) was larger than that of the Searching stage (0.24 and -0.97), which was in turn larger that the Cruising

stage (-0.09 and -1.71). Moreover, most delta power of the Planning stage were significant larger than that of the Cruising stage in right sensorimotor and parietal, and the other condition (male parietal) delta power of the Planning stage (-1.05) was also showed a larger trend than that of Cruising stage (-1.58).

4.2.4. Gender

In the left sensorimotor component, the main effect of Gender was significant ($F(1, 7) = 6.62$, $p < .05$, $\eta_p^2 = .49$) in the gamma1 band power (Figure 17c). No significant interactions were found for Gender and other factors (Table 5b). Males' frequency power (-0.56 was larger than females' (-1.24). In the right sensorimotor component, the main effect of Stage in the gamma1 band power was significant ($F(2, 20) = 7.96$, $p < .01$, $\eta_p^2 = .44$) and there was a significant interaction between Stage and Gender ($F(2, 20) = 7.23$, $p < .01$, $\eta_p^2 = .42$). This interaction was due to the diversity that there was significant Stage difference (the gamma1 power of the Planning stage (-0.60) were larger than that of the Searching (-1.27) and Cruising stages (-1.34) for female but not significant for male.

In the frontal component, although there was no significant difference ($p > .05$) between theta power of Gender, there was still a trend indicated female's theta power (2.88) was larger than male's (1.79). If the frequency band narrowed to 6 and 8 Hz (Figure 17b), this power difference of Gender would reach significant level ($F(1, 11) = 5.07$, $p < .05$, $\eta_p^2 = .32$). And there were also no significant interactions between Gender and other factors for this frequency band. For this high-theta band, females' frequency power (3.61) was larger than males' (2.00).

4.2.5. Landmark

The relative power of Landmark differed for the delta band power across most clusters (Table 5c). The main effects of Landmark were significant for the

delta band power of the frontal ($F(1, 11) = 11.93$, $p < .01$, $\eta_p^2 = .52$), central ($F(1, 8) = 16.09$, $p < .01$, $\eta_p^2 = .67$) and occipital ($F(1, 9) = 10.67$, $p < .01$, $\eta_p^2 = .54$). There were no significant interactions between Landmark and other factors. The frequency power of frontal (Figure 17e), central and occipital (Figure 17f) were larger in the Global landmark (0.46, 0.24 and -0.69) than in the Local landmark (-0.04, -0.15 and -1.26) condition. Further, there was a significant interaction between Stage and Landmark ($F(2, 14) = 3.93$, $p < .05$, $\eta_p^2 = .36$) in left sensorimotor. This interaction was due to the difference that the Global delta power (-0.05) was significant larger than Local power (-0.44) in Planning stage but similar with Local power in Searching (-0.47 vs. -0.44; $p > .05$) and Cruising stages (-0.41 vs. -0.39; $p > .05$). In the right sensorimotor, there were also significant interactions between Structure, Gender and Landmark ($F(1, 10) = 15.05$, $p < .01$, $\eta_p^2 = .60$), and between Structure and Landmark ($F(1, 10) = 21.74$, $p < .001$, $\eta_p^2 = .69$). Post hoc analysis indicated the delta power difference of Landmark only reached significant level (-0.39 for Global; -1.22 for Local; $p < .05$) for male in regular maze but not significant in the other conditions.

4.2.6. Structure

No significant main effect associated with Structure was found (all $p > .05$) for each cluster frequency band. There were only significant interactions between Stage, Gender and Structure ($F(2, 16) = 3.73$, $p < .05$, $\eta_p^2 = .32$), and between Stage and Structure ($F(2, 16) = 6.43$, $p < .01$, $\eta_p^2 = .45$) for the gamma2 band power in central, and there was also a significant interaction between Stage and Structure ($F(2, 18) = 4.26$, $p < .05$, $\eta_p^2 = .32$) and a significant main effect of Stage ($F(2, 18) = 8.97$, $p < .01$, $\eta_p^2 = .50$) for the gamma1 band power in occipital (Table 5d). In the central cluster, these interaction were due to the difference that the gamma2 power was significant larger in the Regular structure (-0.08) than that in the Irregular structure (-0.46) for male in Planning stage but not significant in the other conditions. Because of three numbers of males in this

cluster, this difference was not discussed later. In the occipital cluster, post hoc analysis revealed that the gamma1 band power of Planning stage (-0.29) was larger than that of the Searching (-0.82) and Cruising stages (-0.88) in the Regular structure and this frequency band power of Planning (-0.38) and Cruising stages (-0.44) were larger than that of the Searching stage (-0.80) in the Irregular structure maze. Then the gamma1 band power of Irregular structure was also larger than that of Regular structure during the Cruising stage.
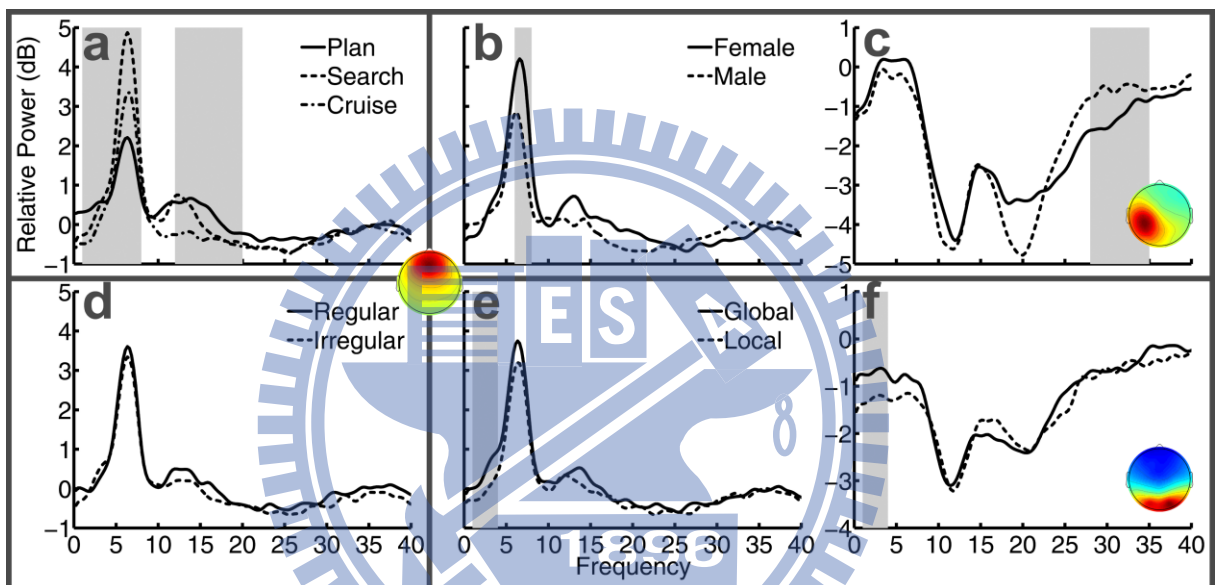
Figure 17. This figure showed the relative power spectra of conditions which included stage (a), gender (b and c), structure (d) and landmark (e and f). The gray areas indicated the power were significant difference (four-way mixed-design ANOVA) during this frequency band. The scalp maps indicated these relative power spectra were from frontal (a, b, d and e), left sensorimotor (c) and occipital (f).

V Discussions

This study performed the wayfinding tasks of learning and retrieval and analyzed the behavior data of learning task as well as EEG signals of retrieval. These results were discussed as follows:

5.1. Advantages of the FlexNavi system

The above experiment provided an example of applying the FlexNavi system in studying the human wayfinding behavior and EEG. We would like to highlight the following features of FlexNavi which distinguish it from other freely available or commercial softwares:

1) Ease of use: FlexNavi requires minimal programming skill on the user's side. The construction of the 3D environment is pretty simple and the behavior of the VR environment can be easily manipulated by specifying parameters in text files. This can save researchers significant amount of time in developing the VR environment for their experiments.

2) Flexibility in available VR: By separating the 3D model and the control modules, FlexNavi allows the user to construct any kind of VR environment that they would like the participant to experience. The complexity of structure and the texture detail of the VR environment can go as far as the user needs. This gives the researchers quite a lot of flexibility.

3) Flexibility in control and interfacing: Navigation in FlexNavi can be achieved by keyboard, joystick, and mouse. It also supports input and output communications from parallel port to synchronize with other facilities such as EEG or MRI scanner.

4) Richly logged information: FlexNavi automatically logs the 3D coordinates, orientation, key presses, time stamps, TTL triggers, and many other details during the experiments, which allows the users to carry out extensive analyses of navigation behavior in the VR.

5) The limitation of the current version of FlexNavi is that it only supports 3ds model which does not render light sources, animation and dynamic 3D model. In addition, it does not yet support user-controlled movement in the z-dimension. These features can be included in the FlexNavi system if future users demand these functionality for their experiments.

With these features, most types of spatial navigation experiments can be easily carried out, be it behavioral or neuroimaging experiments. Besides the example experiment introduced in the current study, we have also used FlexNavi in a few other EEG and fMRI experiments seamlessly.

5.2. Experiment 1: behavior discussions

The current study adopted both overall and fine-grained measures to examine how gender differences in wayfinding are modulated by the type of landmark available in the virtual environment. Two major findings emerged from this investigation: First, the main effects of gender in both overall measures did not converge to reflect the typical superiority of male performance observed in wayfinding tasks. That is, while females spent more time than males in locating targets, both genders were generally equivalent in terms of corrected travel paths. The divergence between the conventional overall measures in the spatial and temporal domains contradicted the close correspondence between these two domains reported in previous studies [62-64]. As already suggested by some researchers, the overall measures, though indicative of overall performance, present a coarse resolution and may miss fine-grained characteristics of wayfinding behavior [53, 65].

Second, the prediction that males would outperform females in the global condition and that females would outperform males in the local condition was only partially confirmed. For the overall measures, both the path and time measures showed landmark type by gender interactions, but the patterns of interaction were different. Regarding the corrected travel path, there was a

tendency for males to travel longer distances than females in both landmark conditions, but the gender difference was not significant for either type of landmark. In terms of travel duration, males did spend less time than females in both landmark conditions, and the gender difference was larger in the global than in the local condition. Although these results are not entirely consistent with the original prediction, they do partially echo the idea that the superior performance of males is more obvious in the global than in the local landmark condition. Regarding the fine-grained measures, TR_{away} showed that females spent a smaller proportion of time than males in traveling away from the target location when local landmarks were available, but there was no gender difference when global landmarks were present. Assuming that less time moving away from the target location indicates better performance, this result is consistent with the prediction of female superiority in the local landmark condition, though not with the prediction of male superiority in the global landmark condition. $ROT_{no-translation}$ showed a tendency for females to rotate more angles than males when they made stops, and this gender difference was more prominent in the global than in the local condition. Assuming that less rotation indicates better performance, this result is consistent with the prediction of male superiority in the global landmark condition, though not with the prediction of female superiority in the local landmark condition.

In the following sections, three issues raised in the preceding summary will be discussed in turn: 1) Why did the overall spatial measure diverge from the temporal measure? 2) How do results from the overall and fine-grained measures conjointly form a complete picture of gender differences in wayfinding? 3) How does landmark type moderate gender differences in wayfinding?

5.2.1. Divergence between overall spatial and temporal measures

Two non-exclusive explanations of the divergent results from the overall

spatial and temporal measures are provided here. The first explanation is not directly related to wayfinding ability *per se*. The discrepancy between spatial and temporal measures may simply result from the more advanced computer skills of male participants. Coluccia and Louse (2004) suggested that male advantage is dramatically enhanced (males outperforming females in 57 % to 86 % of the experiments reviewed) in VEs when the participants had the opportunity to interact actively with the computerized environment during wayfinding. This is likely due to a higher familiarity with the virtual environment among males because statistically, males play more video games than do females [cf. 47, 66]. We noted that all male participants were enrolled in departments related to engineering, whereas only seven female participants were from those departments. Furthermore, twelve males reported playing video games frequently, whereas only six females reported the same. Because males might already be quite familiar with the computer interface, they may not have much room for improvement in speed. Consistent with this account, a trend in our results (though not remarkable) seems to suggest that wayfinding time improves more from the first half of trials to the second half in females than in males (Figure 13b). Thus, the males' advantage in time may reflect their superior skills in operating the computer interface, but their familiarity with the computer interface may be independent of their cognitive map, which was more directly reflected by the path measure.

The second explanation of the divergent results is that females and males adopted different strategies when performing the wayfinding task. Females may have adopted a less exploratory strategy than males did; they tended to stay in the same locations to look around rather than continuing to move, as evidenced by their higher $TR_{no\text{-}translation}$ and $ROT_{no\text{-}translation}$. By contrast, males preferred to cover a larger area in the virtual environment. A higher proportion of time on the move also led to more changes in orientation while moving (indicated by males'

higher ROT$_{translation}$). Continuously moving did not make males more effective wayfinders. Based on TR$_{away}$, it seems that males spent a slightly higher proportion of time moving away from the target location than did females. However, given the fact that no dead end existed in the grid-like environment, this strategy increased the males' chances of finding the target within a shorter amount of time. By monitoring the gaze of participants in a virtual version of the Morris water maze experiment, Mueller et al. [34] demonstrated that females showed initially longer fixation durations and increases in pupil diameter than males did when looking for the path to the hidden platform. Perhaps when finding their way, females require frequent stops to look around and compare the flow of visual scenes with their spatial representations of the environment.

5.2.2. Integrating overall and fine-grained measures of wayfinding performance

This latter interpretation of the gender difference integrates results from the fine-grained measures. Numerous studies on wayfinding have adopted overall travel duration [40, 47, 64, 67-68], length of travel path [69], or both [31, 34, 63, 70-71] as an indicator of performance. In this experiment, the overall travel duration indicated a clear male advantage (shorter travel time), similar to the findings of several previous studies in certain contexts of wayfinding [47, 64, 68]. The results of the corrected path measure were also similar to the results of some wayfinding studies [71] that demonstrated no gender difference. The divergence between spatial and temporal measures in the current study suggests that both should be analyzed. Although these measures usually concur, perfect correlation between them is not always guaranteed. The strength of consistency between these two types of measures may depend on the geometric or visual features of the environment or on the idiosyncratic wayfinding strategies adopted by the participants. Merely relying on one type of measure may lead to biased interpretations of the differences between groups or conditions. When the overall measures diverge, researchers must examine information regarding

metrics at other levels for an accurate interpretation of participant performance [see 53, for comprehensive illustrations].

5.2.3. Influences of landmark types on gender differences

It is also worth noting how wayfinding performance differed between the global and local landmark conditions. As an overall trend, participants traveled longer paths in the local than in the global landmark environment. This was most likely due to the fact that global landmarks could be constantly seen in the mazes and used as visual anchors when computing orientation and heading. By contrast, participants had to move around to search for local landmarks, which made the travel distance longer in the local landmark condition than in the global landmark condition. Analyses of overall measures (Figure 13) also indicated that males benefited more from the presence of global landmarks than did females. Furthermore, it seemed that global landmarks even slowed down female performance. These results are consistent with previous findings that females and males are sensitive to the local and global aspects of the environment, respectively [38, 55-58].

Aside from the global/local landmark processing tendencies of each gender group, a different but not mutually exclusive interpretation based on gender-specific strategies of movement in the VE is also possible. Participants walked away from the target location (TR_{away}; Figure 14a) and continued moving ($TR_{no-translation}$, Figure 14b) for longer portions of time under the local than under the global landmark condition. These general differences between global and local landmarks were also mediated by gender and trial blocks. From the significant three-way interaction observed for corrected travel distance and TR_{away}, we found larger differences between the first and second halves of the trials for the local landmark condition only for males. Males had disproportionately larger travel distances and proportions of time of moving away from targets in the early phase of wayfinding in the environment with local

landmarks. This can be attributed to the more exploratory wayfinding strategy that males use to reorient themselves in the VE [58], especially at the beginning of the local landmark condition. When navigating the environment with local landmarks, seeing a particular landmark is difficult because it is only visible from certain locations and perspectives. This characteristic may have bolstered the male tendency to continue moving, especially at the beginning of the experiment, when they were still not familiar with the environment.

5.3. Experiment 2: EEG discussions

In general, the frontal cluster showed the most modulations across frequency bands associated with factors examined in the current experiment: We found increases of frontal theta band power during the Searching stage and suppression of this frequency band during the Cruising stage; there was also suppression of frontal beta1 band power, suppression of frontal, parietal and occipital delta power and suppression of parietal and occipital theta power during the Cruising stage. The ERSPs of the other components showed alpha blocking (or suppression) at the peak alpha frequency (about 10 Hz) and its first harmonic (20 Hz). Larger frontal high theta and smaller left sensorimotor gamma1 band power were found in females than male. Then the Landmark type difference was showed in the frontal, central and occipital power of delta band. The regularity of the environmental geometry did not lead to observable main differences in any spectral power across conditions but showed larger occipital gamma1 band power during Cruising stage in the Irregular structure. Table 6 summarized the connections between our results and literatures.

Table 6. Connections with literatures

Factor	Cluster	Band power	Literatures
Stage	Frontal	Theta increase (search > cruise > plan)	Navigation (Jaiswal, et al., 2010; Kober & Neuper, 2011; Laukka, et al., 1995; Weidemann, et al., 2009); Cerebral challenge (Jaiswal, et al., 2010; Kahana, et al., 1999); Mental imagery of navigation (Li, et al., 2009);
		Beta increase (plan, search > crusie)	Learning and memory (Caplan, et al., 2007; Macaulay, et al., 2004; Onton, et al., 2005; Tallon-Baudry, et al., 1999); Mental calculation (Fernandez, et al., 1995; Lin, et al., 2011)
		Beta suppression (crusie < plan, search)	Relaxation (Diego, et al., 2004; Field, et al., 1996; G. D. Jacobs, 2001; G. D. Jacobs, et al., 1996; Macaulay, et al., 2004)
	Central, sensorimotor, parietal and occipital	Alpha and beta suppression (search, cruise < plan)	Motor-related mu blocking (Pfurtscheller, et al. 1979; Pfurtscheller, et al., 1996); Optical flow (Gramann, et al., 2010); Visual perception (Pfurtscheller, et al., 1996; Vanni, et al., 1997); Visuospatial attention (Fu, et al., 2001; Thut, et al., 2006).
	Frontal, parietal and occipital	Delta increase (plan > cruise)	Salience of the target stimulus (Knyazev, 2007); Signal detection and decision making (Basar, et al., 2000); Attention to internal processing (Harmony, et al., 1996).
	Parietal and occipital	Theta suppression (cruise < search)	Alertness (Beatty, et al., 1974; Lin, et al., 2010).
Gender	Frontal	Theta increase (female > male)	Navigation (Kober, et al., 2011); Cerebral effort (Jaiswal, et al., 2010; Kahana, et al., 1999); Usage of frontal area (Gron, et al., 2000); Dependence on landmark (Sandstrom, et al., 1998).
	Left sensorimotor	Gamma suppression (female < male)	Declarative memory formation (Fell, et al., 2001; Sederberg, et al., 2007).
Landmark	Frontal, central, right sensorimotor and occipital	Delta increase (global > local)	Larger stimulus field (Bartl, et al., 1978; Flamm, 1974; Hennerici, et al., 1977; Katsumi, et al., 1988; Korth, et al., 1997; Sakaue, et al., 1990).

Structure	Occipital	Gamma increase (irregular > regular)	Receipt of moving consistency of objects (Muller, et al., 2000; Lutzenberger, et al., 1995); Search of hidden object (Tallon-Baudry, et al., 1997); Recognition of shape (Tallon-Baudry, et al., 1996; Yuval-Greenberg, et al., 2008); Exploration of spatial information (White, et al., 2011).

5.3.1. Frontal Theta

The increasing frontal theta power during navigation and searching was consistent with previous EEG navigation studies [9-11, 13]. Specifically, frontal region showed increased activation in response to increased cerebral challenge during encoding in comparison to retrieval of visual–spatial information [9]. Mental imagery of navigation also leads to larger theta power than does digit imagery task [12].

Although many studies have indicated hippocampal activation during navigation task [16-20, 24, 26], many imaging studies identified the crucial role of frontal area in navigation. Frontal area was the most active area in spatial working memory task [16, 26, 72-74], and also activated during planning, decision making [17-20, 27] and holding on-line goal related information [24-25, 75]. Ciaramelli [76] reported that a patient with ventromedial prefrontal damage would head toward more familiar locations and then lost his way while navigating. It could be that the ventromedial prefrontal cortex serves to coordinate abilities related to navigation.

5.3.2. Mu and Alpha Blocking

The alpha suppression of sensorimotor components was the typical motor-related mu blocking over the Rolandic regions [77-78]. During our experiment, participants must keep button control to search targets, and therefore induced mu blocking. Although the alpha blocking of parietal and

occipital components might be influenced from the motor control, this alpha blocking was consistent with previous navigation study during only optical flow procedure [79]. Furthermore, the experiments of visual perception [78, 80] or visuospatial attention [81-82] revealed that alpha suppressed when processing visual stimulus or attending to the spatial location on which the forthcoming visual target could appear. Therefore, the reason for alpha blocking of parietal and occipital components in current study might be that participants would keep attention to the locations of landmarks and targets and process the perception of optical flow during search targets.

5.3.3. Stage

This study separated navigation process into Planning, Searching and Cruising stages between targets appeared and found. During these stages, we found frontal theta power was increase then suppression. This change was similar to the taxi study [13] whose theta activity in response to nontarget store views during searching process was larger than target store views. This might be occurred according to difference spatial process or cerebral challenge [8-9]. Present study systematically found the cruise onset which was a location on the familiar path to target. Before Cruising stage, participants would keep comparing environment and landmarks with built inner map and memorized spatial information to search the way to target. During Cruising stage, they only followed the decided way then reached target location. This might also cause the change of frontal beta band power which was related to mental activity.

Previous studies indicated that relaxation would decrease the frontal beta power [83-87] while learning, memory [87-90] and mental calculation [91-92] would increase the frontal beta power. At the search beginning, participants would need recalling memory to find the relations between current position and landmarks in the limited duration, and this would increase mental stress. They would relax when they had planed the way to target. According to above mental

activity, the frontal beta power of Planning and Searching stages was larger than that of Cruising stage.

The difference of frontal, parietal and occipital delta band power might be due to the event-related potential between 100 and 1000 ms after target picture appeared (Figure 18). Actually, the delta power (Figure 17) and the event-related potential (Figure 18) occurred during Planning stage at each cluster. Although event-related potential also occurred at the beginning of search and translation (due to the large change of view), the amplitudes were not larger in the Searching than that in the Planning stage. Knyazev [93, for a review] indicated that the amplitude of the P300 increases with the motivational relevance of the task or the salience of the target stimulus and the P300 amplitude were correlated positively with delta power. And the increase in delta activity may be related to signal detection, decision making [94] and attention to internal processing (calculation and short-term memory of digit) during the performance of mental task [95]. In present study, participants would expect the appearance of targets then think the target directions to move. This would cause more delta activity during Planning than Searching and Cruising stages.

There were also differences of parietal and occipital theta band power between Searching and Cruising stages. This would be due to the wide band influence of alpha blocking. In general, the posterior theta power was associated with alertness. The suppression of theta activity enhanced monitoring task efficiency [96] and improved driving performance in driving simulator [97]. Therefore, participants would focus to the way to target location according to their defined path and kept waiting the target appearance during Cruising stage then suppress the theta power of parietal and occipital.
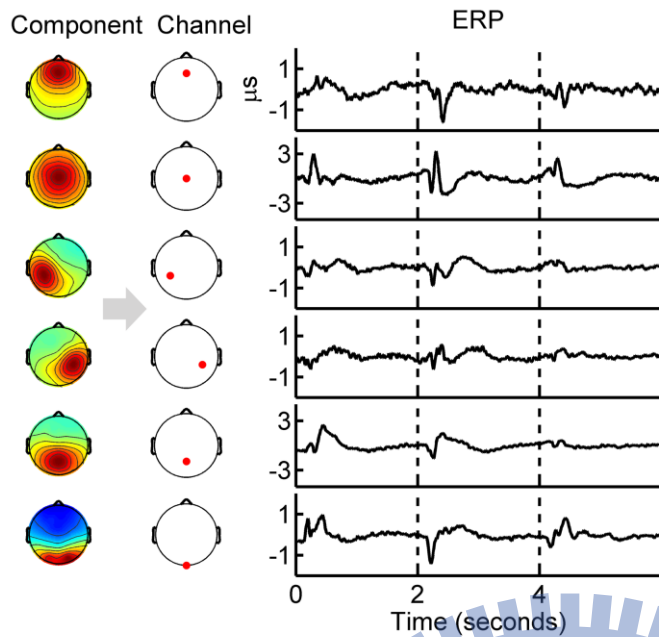
Figure 18.   This figure revealed the event-related potential of clusters which were back projected from components to channels (FZ, CZ, CP3, CP4, PZ and OZ) around the Planning stage (2 - 4 s).

5.3.4. Gender

The frontal theta power difference of Gender was also appeared in previous EEG study whose theta synchronization was larger in females than that in males during searching for target [10]. This might be due to the different cerebral effort which females required more to do navigation task [8-9]. Further, functional image study revealed distinct activation of the left hippocampus in males, whereas females consistently recruited right parietal and right prefrontal cortex [16]. This reflected the behavior study which demonstrated females rely predominantly on landmark information, while males more readily use both landmark and geometric information [47]. Accordingly, females activated frontal area to process working memory to keep holding landmark information, and males activated left hippocampus to process multiple geometric information [16]. Therefore, females might generate larger frontal theta power than males during navigation with landmarks.

Although Gender difference in low gamma band power of left sensorimotor component might be due to the button control, the difference was not significant at press frequency (1.96 for females vs. 2.05 for males; $p > .05$) and times (15.3 vs. 15.2; $p > .05$) each period. Moreover, the depth-EEG experiment of declarative memory formation revealed that participants successfully recalled words would decrease low gamma power [98-99]. Maybe females depended on more landmark information then used words to memorize them. Therefore, when retrieving memory, females might decrease larger low gamma power than males.

5.3.5. Landmark

There was little literature investigated the cerebral difference between Global and Local landmarks during spatial navigation. And the functional image study demonstrated that participants activated more brain area when receiving wild field visual stimulus [100]. Further, EEG studies investigated that the amplitude of event related potential of visual area was larger in the experiment with larger stimulus field [101-106]. This event related potential belonged to low frequency, and would increase the power of delta band. The different power reflected on Landmark condition might be due to the requisition of continuously gazing at Global or Local landmarks for catching their current positions and directions during search. Therefore, navigation with Global landmarks (gigantic architectures) might induce larger delta power than Local landmarks (pictures).

5.3.6. Structure

The power difference of Structure was in the occipital gamma band during Cruising stage. Previous EEG researches indicated the occipital gamma increase was associated with visual processing such as: receipt of moving consistency of objects [107] or lines [108], search of hidden object in picture [109] and recognition of shape [110-111]. This gamma activity would be also associated

with exploration of spatial information [112]. Further, during the Cruising stage, participants would rapidly move along the defined route to search target picture from these visual scenes then receive the same direction of larger visual flow during moving. Therefore, they might process more visual objects and explore additional spatial information in the Irregular maze then induce larger occipital gamma power during the Cruising stage.

VI Conclusions

To conclude, the FlexNavi system offers an easy, flexible, and openly accessible way for conducting experiments on spatial navigation. Researchers could design VR environments with complicated spatial structures and arrange various sequences of events in the experiment without having to acquire programming skills. We hope the introduction of the FlexNavi system will facilitate future behavioral and neuroimaging studies on spatial navigation.

This study also used FlexNavi to build the virtual maze to investigated gender behavior differences during learning to find targets and EEG power differences during retrieving spatial memory to find targets after learning. Contextual features of the environment, such as the types of available landmarks, modulate gender differences in wayfinding behavior. This is particularly obvious at the early phase of learning to find the way in a novel virtual environment. Although not all dependent measures confirmed our initial hypothesis of the gender by landmark type interaction, the distinct patterns of results from different measures actually provided complementary information. Generally, males tended to engage in a more exploratory mode of wayfinding, which led to quicker moves but not necessarily to optimal routes. By contrast, females adopted a more conservative strategy by making more stops to change their viewing orientation, which led to slower moves but not fewer detours. These gender differences were most obvious for VEs with local landmarks, most likely due to the different strategies adopted during wayfinding; males learned the map from a configural perspective, whereas females focused on local features [58]. Future wayfinding studies on gender or other variables of individual differences could benefit from analyzing both the overall and fine-grained measures of performance, which would reduce the risk of biased conclusions on wayfinding ability in different subject groups or environmental contexts.

In the EEG analysis, present study systematically separated the process of

search target into Planning, Searching and Cruising stages, and revealed the frontal theta and beta band power change related to stages of different requisition of cerebral effort and mental activity. The result of Gender difference supported female dependence on landmarks. And navigation with Global landmarks might extend stimulus field to induce larger delta power than with Local landmarks. Then navigating rapidly in Irregular structure maze would need more visual processing and reflect the occipital gamma activity.

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Appendix 1. ANOVAs table of all clusters and frequency bands

		Main effect				Interaction												Description	
Cluster	Band	Stage	Structure	Landmark	Gender	stage*landmark	*strucure*gender	stage*structure *landanmark	stage*gender *structure	stage*gender *landmark	structure*gender *landmark	stage*structure	stage*landmark	stage*gender	structure*landmark	structure*gender	landmark*gender	Main	Posthoc
Frontal	δ	**		*														p>s>c; g>l	
	θ	*																s>c>p	
	α												*						
	β1	**																p,s>c	
	β2	*											*						G p>c
	γ1																		
	γ2																		
Central	δ		*															g>l	
	θ																		
	α	**												*					M p>c
	β1	*																p>s	
	β2	*						*		*							*		RG p>s,c; IG p>s
	γ1	*																	
	γ2					*							*					MP r>i	
Left sensorimotor	δ												*						P g>l
	θ																		
	α	**																p>s,c	
	β1	**																p>s,c	
	β2	**																p>s,c	
	γ1				*													m>f	
	γ2																		

Cluster	Band	Main effect				Interaction											Description	
		Stage	Structure	Landmark	Gender	stage*landmark *strucure*gender	stage*structure *landanmark	stage*gender *structure	stage*gender *landmark	structure*gender *landmark	stage*structure	stage*landmark	stage*gender	structure*landmark	structure*gender	landmark*gender	Main	Posthoc
Right sensorimotor	δ	**								*		*		**				ML i>r; MR g>l; G p>c; L p>s,c
	θ													*				
	α	**				*						*		**				FLR p>s,c; FGR, FGI, FLI p>c
	β1	**												**				F p>s>c; M p>s,c
	β2	**					*											RG, RL, IG p>s; IL p>c
	γ1	*												**				F p>s,c
	γ2					*								*				
Parietal	δ	*												*				F p>c
	θ	*															s>c	
	α	**															p,s>c	
	β1	**												*				G p>s,c; L p>c
	β2					*												
	γ1					*												
	γ2																	
Occipital	δ	*		*													p>s>c; g>l	
	θ	*															p>s>c	
	α	**															p>s>c	
	β1	**												*				F p>s,c; M p>s>c
	β2	**					*		*				*	*				FL p>c; FG, MG, ML p>s,c; RG, RL, IG, IL p>s,c
	γ1	*											*					R p>s,c; I p,c>s; C i>r
	γ2																	

*p<.05, **p<.001

P: plan, S: search, C: cruise, G: global, L: local, F: female, M: male, R: regular and I: irregular.

The capital letter meant the comparison was executed in this condition, and the lower case indicated the significant difference (p < .05) and relations between these conditions. Only significant differences were shown in the table.

There were significant main effects and interactions of stage in the frontal alpha, right sensorimotor theta and gamma2, parietal beta2 and gamma1 but the post hoc analysis revealed no significant difference between stages. And that there was significant main effect and interaction of landmark in the central beta2 but the post hoc analysis also revealed no significant difference between landmark types. Therefore the asterisks of above cluster frequency bands were excluded from this table.