OpenMaze: An Open-Source Toolbox for Creating Virtual Navigation Experiments

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Abstract

Incorporating 3D virtual environments into psychological experiments offers an innovative solution for balancing experimental control and ecological validity. Their flexible application to virtual navigation experiments, however, has been limited because accessible development tools best support only a subset of desirable task design features. We created OpenMaze, an open-source toolbox for the Unity game engine, to overcome this barrier. OpenMaze offers researchers the ability to conduct a wide range of first-person spatial navigation experiment paradigms in fully customized 3D environments. Crucially, because all experiments are defined using human-readable configuration files, our toolbox allows even those with no prior coding experience to build bespoke tasks. OpenMaze is also compatible with a variety of input devices and operating systems, broadening its possible applications. To demonstrate its advantages and limitations, we review and contrast other available software options before providing an overview of our design objectives, and walking the reader through the process of building an experiment in OpenMaze.

Introduction

Examples of how available technology shapes the insights we can glean from behavioral experiments are many, ranging from response time recordings that reveal the timing of cognition (Donders, 1869) to tools that precisely control photon emissions allowing us to understand the limits of human vision (Hecht, Shlaer, & Pirenne, 1942). More recently, the joint development of realistic 3D rendering capabilities and virtual physics engines has enabled the construction of virtual environment (VE) experiments. Here, we define VE experiments as those in which participants can navigate from a first-person perspective through a 3D spatial environment. Of relevance to cognitive psychologists, this technology provides an innovative way to balance trade-offs between experimental control and ecological validity; a researcher can test how people interact with naturalistic (often immersive) settings that are nevertheless fully under experimental control. And, by eliciting cognitive processes similar to those engaged during real world navigation (De Kort, Ijsselstein, Kooijman, & Schuurmans, 2003; Lloyd, Persaud, & Powell, 2009; Wilson, Foreman, & Tlauka, 1996), VE experiments provide an inroad to studying phenomena – like allocentric spatial memory – that cannot otherwise be studied in a laboratory setting (see Ekstrom et al., 2014; Herweg & Kahana, 2018). Further, these experiments are compatible with the many neuroimaging and neurostimulation methods that require immobility.

Illustrating their power in just one domain, VE experiments have yielded many translational insights into spatial memory. These include hippocampal contributions to human navigation (Maguire et al., 2002), evidence of place cells (Ekstrom et al., 2003; Miller et al., 2013), and entorhinal grid cells (Jacobs et al., 2013; Nadasdy et al., 2017)—all of which have important parallels to neurophysiological findings in animal models (see Hartley et al., 2014). VE

experiments also hold promise for clinical applications. For example, deficits in virtual navigation have been linked to preclinical Alzheimer’s Disease (Coughlan, 2018; Serino, 2015; Tu & Pai, 2006), demonstrating that VE tasks may one day prove to be important diagnostic tools.

The adoption of VE technology in experiments has largely been facilitated by advances in video game development engines – a technology that streamlines video game creation. Luckily for experimental research, contemporary game engines provide many of the tools necessary for creating VE experiments, including 3D rendering, physics engines, and stimulus creation tools. Even more appealing, many of these engines are free to use. Indeed, game engines have been successfully used to build custom VE experiment tasks (examples include: Deuker et al., 2016; Tsitsiklis et al., 2019). The technical expertise required to build experiments directly within game engines, however, can be prohibitive to many research groups.

To address this challenge, we developed OpenMaze, a flexible yet accessible open-source toolbox for creating first-person navigation VE experiments with the Unity game development engine. Researchers with no programming experience can use OpenMaze to turn the environments that they build with Unity software into bespoke spatial navigation experiments. In the sections that follow we first review a sampling of existing approaches, exploring some of the advantages and disadvantages of each. We then lead the reader through the design objectives of OpenMaze, step-by-step examples of its use, and conclude by exploring future development possibilities.

Review of Existing Approaches

Game Engines

Researchers with sufficient programming expertise can build highly customized experiments directly in game development engines. Two of the most popular options among researchers are Unity software (Unity Technologies; example experiments: Nadasdy et al., 2017; Tsitsiklis et al., 2020) and Unreal software (Epic Games, Inc; example experiments: Deuker et al., 2014; Steemers et al., 2016; West et al., 2017). Both engines provide built-in, drag-and-drop/point-and-click graphical user interfaces (GUIs) for creating highly customizable environments and stimuli. Additionally, both engines have marketplaces with large selections of compatible 3D models. However, because game engines were not built with experiment presentation in mind, they lack some of even the most basic features required for an experimentalist (e.g., data output). Thus, experimental tasks can only be implemented by writing custom code in C#/JavaScript (Unity) or C++ (Unreal). And, because the resulting codebases are tailored to the researcher's project—and thus idiosyncratic—other researchers may struggle to use them in replication or extension efforts. So, while building experiments directly in game development engines affords remarkable task customization, the process can be inefficient, prohibitively technical, and antithetical to the mission of open science and replicability.

VE Experiment Design Programs

We next discuss software tailored for building VE experiments. We make the distinction between design *programs* (this section), or standalone applications with their own interface which may be built on top of game engines but *do not* require the user to interact with the game

engine directly; and *toolboxes* (next section), which extend game engine functionality but are not standalone applications, and therefore *do* require the user to directly interact with the game engine.

One popular design program is MazeSuite (Ayaz et al., 2008), which provides a simple point-and-click interface for creating tasks in which participants navigate through enclosed routes. It includes graphical tools for drawing maze walls, inserting waypoints and objects, combining mazes into an experiment, and analyzing behavior. By specializing in maze paradigms, this tool is particularly well-suited to translating paradigms used in rodent models (e.g., Morris Maze, Radial Arm Maze) for human participants. To increase task complexity, MazeSuite includes dynamic objects (that add and remove a participant's points when they interact with them), which can be combined with conditional end regions (that terminate trials only after collecting enough points). MazeSuite also has integrated parallel and serial port settings to facilitate synchronization with external data collection devices. However, some users may find the graphics limited compared to options supported by contemporary game engines. Further, the program only runs on Windows computers and its protected codebase restricts users from making even minor changes to functionality. Overall, MazeSuite is therefore well-suited for users with limited or no programming experience who are interested in efficiently building maze navigation experiments and have access to a Windows machine.

Virtual SILCton (Weisberg et al., 2014) a Unity-based experiment suite, is a tool designed to assess individual differences in spatial navigation abilities. It includes a route integration task within a virtual environment modeled after Temple University's Ambler campus. This experimental task is complemented by a variety of well-validated questionnaires (e.g., for assessing sense of direction, spatial abilities) and spatial tasks (e.g., distance and direction

judgements, mental rotation, and map placements). Experimenters can select from this battery of assessments, customize their order, and tweak some parameters. Because the tasks are built in the Unity game engine, graphics and physics engines are cutting-edge. Moreover, tasks can be administered online and, because they are all pre-built, setting up an experiment requires minimal work. This convenience does come at a cost to flexibility; Virtual SILCton is not designed for custom task creation.

VE Experiment Toolboxes

VE experiment toolboxes offer an appealing balance between the costs and benefits of working directly with a game development engine and using stand-alone VE experiment design programs. They add VE experiment design functionality to game development engines. Users can, thus, harness video game features, like advanced graphics and stimulus development tools, without having to write custom code to support experiment-specific features, like data logging. Here we briefly review the strengths and limitations of several toolboxes before introducing our toolbox: OpenMaze.

PandaEPL (Solway & Kahana, 2014) is a general-purpose, Python-based programming library of classes and functions designed for creating wayfinding tasks using the Panda3D graphics engine (Goslin & Mine, 2004). Advantageously, Python is already widely used in the field (e.g., <https://www.psychopy.org/>) so experimenters already proficient in this language may prefer this toolbox to alternatives that use graphical interfaces. However, even those who prefer coding to point-and-click solutions may find the lack of integrated GUI cumbersome, as environments and object stimuli must first be created using third party 3D modelling software (e.g., Blender, 3ds Max, or Maya). Transferring stimuli between programs to make even minor changes may slow

experiment development. Furthermore, the Unity game engine offers more extensive documentation and a larger userbase than Panda3D, both of which are crucial for troubleshooting.

More recently, a handful of toolboxes have been developed to enable experiment building within the Unity game engine. One offering, VREX (Virtual Reality Experiments; Vasser et al., 2017), creates immersive object change blindness and false memory experiments. VREX provides its own GUI to simplify stimulus creation in Unity. This interface is optimized for (but restricted to) the building of apartment-like settings comprised of prefabricated rectangular rooms and corridors. Custom models can be added, though, using the standard Unity import pipeline. After building and furnishing an apartment, experimenters can then configure how it will be used in one of the two supported tasks. While the restricted environments and tasks limits the generalizability of this tool out-of-the-box, VREX is open-source and provides template scripts to help advanced users create their own tasks.

The Experiments in Virtual Environments (EVE) framework (Grübel et al., 2017) provides a more general-purpose solution for experiment design. EVE includes a limited number of ready-to-use environments that can be customized within the Unity GUI. While editing stimuli is somewhat more complicated in the Unity GUI than in the purpose-specific GUI provided by VREX, Unity affords greater customization of environments and stimuli. Many critical experiment functions are supported by EVE's inclusion of "virtual sensors" within an environment that can serve as waypoints, goals, barriers, entrances, and exits. Different environments with their own task features can then be sequenced into an experiment. Notably, EVE also provides pop-up questionnaires to collect subjective judgements during a task, as well

as separate standardized questionnaires and common tasks (e.g., judgements of relative direction). Additionally, EVE supports the integration of certain eye tracking, physiological recording, and virtual reality (VR) systems. While this flexible framework can support a variety of spatial navigation tasks, its use of Structured Query Language (SQL) databases for logging is only configured for Windows computers. Users are also required to install SQL, creating additional overhead to use the software. Fortunately, EVE has an integrated R package for data analysis so that users need not be familiar with SQL syntax to work with their output.

The Landmarks (Starrett et al., 2020) package uses a similar approach to EVE to support a variety of spatial navigation tasks. A user with no programming background can access Landmarks' prefabricated tasks through the Unity GUI. These tasks include spatial navigation, map learning, judgements of relative direction, and orientation-dependent pointing tasks, as well as standardized navigation questionnaires. The Unity GUI can be used to customize the environment and stimuli; the integrated Landmarks GUI can be used to customize some task parameters and sequence tasks to create an experiment. Like EVE, Landmarks also uses preconfigured objects, called "GameObjects," that add task functions. This allows more advanced users to further customize their tasks by editing or creating their own GameObjects. Those comfortable with C# can use template scripts to build their own tasks and functionality. Additionally, Landmarks provides out-of-the-box tools for integrating VR and electroencephalography (EEG) devices, runs across multiple operating systems, and outputs data in easy to manage comma-separated values (CSV) files. This framework is well suited for researchers who want to quickly generate standard navigation tasks using custom environments and collectable objects. Some researchers, however, may find that while the tasks autogenerated

by Landmarks are too rigid, they themselves lack the technical skills required to successfully modify them.

In summary, the last few years have seen significant advances in VE experiment toolboxes. Thanks to its excellent documentation, active user community, and cutting-edge graphics and physics engines, the Unity game engine has become the preferred platform for these toolboxes. Recent toolboxes, like EVE and Landmarks, have made significant inroads to supporting a wide array of task options. To achieve this flexibility, these tools start with a set of commonly used tasks as templates, with customization enabled by adjusting parameters and stimuli. This solution enables researchers with minimal programming experience to efficiently create an array of different types of tasks. However, this template approach means that programming is still necessary to build tasks that do not fit the mold. In the next section, we describe how we designed OpenMaze to address this gap.

The OpenMaze Toolbox

We developed OpenMaze with the overarching objective of giving researchers with minimal programming experience the free and flexible tools that they need to build VE navigation tasks from the ground up. Rather than fitting a task to a template, we envisioned a framework that supplies common experiment components which researchers combine to generate their desired task structure. With this objective in mind, OpenMaze provides modular navigation task components and a framework for flexibly combining components within a hierarchical task structure. We prioritized the implementation of this ambitious vision of design flexibility within the realm of first-person navigation tasks, and therefore opted to not support an array of other specialized spatial cognition tasks, like judgments of relative direction and map learning.

OpenMaze will therefore be an attractive option for researchers looking to efficiently build atypical, first-person navigation experiments.

Design Objectives and Overview

To achieve our objective of developing a flexible, modular toolbox, we identified the experiment building blocks that are commonly used in first-person navigation experiments. The components fall within a hierarchy, visualized in Fig. 1. The lowest level of our experiment hierarchy includes four building blocks that can be combined to generate a wide variety of task trials: *Scenes*, *Goals*, *Landmarks*, *Enclosures*. The first, and only compulsory, component is the

Figure 1: *OpenMaze Experiment Hierarchy*

Unity-compatible 3D models or image files can be defined as *Goals* or *Landmarks* for use as interactive task or environment stimuli, respectively. Optional *Enclosures* confine participant movement. *Task Trials* are then created by placing different combinations of *Goals*, *Landmarks*, and *Enclosures*, into the *Scenes* that are generated using Unity. Image files can also be presented as *Instruction/Cue Screen Trials*. *Blocks* then dictate the order in which *Trials* are presented.

virtual environment in which the task is performed, called a Scene. With full customization in mind, OpenMaze provides users with an empty Scene along with tutorials on how to use the Unity GUI to build a rich 3D environment. To enable task customization, we also supply interactive objects, called *Goals*. Like virtual sensors in EVE and GameObjects in Landmarks, OpenMaze’s Goals enable critical task functions, like trial termination, point earning, and waypoints. Rather than creating prefabricated objects to serve this purpose, though, in OpenMaze any 3D model or 2D image can serve as a Goal. Further, any combination of Goals can be used in a trial, providing another layer of flexibility. Lastly, to facilitate the systematic modification of Scenes on a trial-by-trial basis, we also provide users with Landmarks and Enclosures. Landmarks add objects (e.g., a building, mountain, shape) to a base Scene; Enclosures add a customizable arena that restricts participant movement. We designed OpenMaze to combine these lowest level components hierarchically such that, Goals, Landmarks, and Enclosures are combined within a Scene to create a *Trial*. Trials are then combined within *Blocks*, which are arranged to generate a full experiment.

To achieve our objective of making a toolbox that is accessible to those with little or no programming experience, OpenMaze allows researchers to configure this experiment hierarchy using JavaScript Object Notation (JSON) files (Fig. 2), which are then read by OpenMaze source code. JSON is a data format that structures information in a human-readable way, requiring little expertise to decipher. Our Configuration Files contain sections for specifying the attributes of each of the configurable experiment components: Blocks; Trials; Goals; Landmarks; and Enclosures. Note that Scenes do not have a section because they are fully customized within the Unity GUI. Within each section, users define a numbered list of each object type (e.g., the five Goals used in an experiment) and set the attributes of each (e.g., the image file, desired position,

and size). For added task flexibility, Trials and Blocks include attributes, like character starting position, trial termination conditions, and trial selection procedures.

We chose to use JSON configuration files in OpenMaze instead of a GUI interface because it better aligned with our primary objective of task flexibility. GUIs are well suited to configuring

Figure 2: Configuration File Example

Configuration files are divided into five sections (*Blocks*, *Trials*, *Goals*, *Landmarks*, and *Enclosures*). Data structures are used to create experiment objects of each type using section specific attribute-value pairings.

template tasks. When each task has a restricted and well-defined set of attributes, drop-down dialogues are a convenient means to select among options. Our philosophy in building OpenMaze, by contrast, leaves the task structure up to the experimenter. Trials can contain any combination and number of Goals, Enclosures, and Landmarks. And, any number of Trials can be combined in any order to create the experiment. Configuration files are well suited to this open-ended structure.

JSON configuration files also offer some advantages over GUIs, chief among which is reproducibility. Having a written record of all task decisions that can be easily sent to collaborators and other scientists facilitates the sharing and evaluation of experiment materials. Even within an experiment, this reproducibility facilitates the development of experimental conditions and counterbalancing schemes. Rather than recreating a series of button presses, the experimenter can simply edit copies of the configuration file. Additionally, because JSON syntax is human-readable, once a user is comfortable with it, they may find editing these text files more convenient than working with a GUI. Users with programming backgrounds can also use their preferred language to write scripts to automate configuration file generation or editing.

Some users, however, may find configuration files more difficult to manage than a GUI, which are generally considered more accessible. For instance, while reading and writing JSON formats does not require coding expertise, it does require strict syntax. Like writing in a programming language, even minor syntax errors (e.g., a missing comma or bracket) will result in an error. To avoid such errors, we recommend using a text editor with JSON format-checking (i.e., linter; recommendations can be found on the OpenMaze website). We also provide a configuration file template, which includes examples of each experiment design feature. Researchers who

nevertheless are uncomfortable learning JSON syntax may find alternative GUI-based options, like Landmarks and EVE, preferable to OpenMaze.

Having broadly reviewed our objectives and decisions that went into OpenMaze's design, we now walk the reader through the steps required to build an experiment using OpenMaze.

Step-By-Step Implementation

Step 1: Download, Install, and Setup

OpenMaze requires three pieces of software. First, the OpenMaze toolbox can be downloaded from the project's GitHub public repository (<https://github.com/DuncanLab/OpenMaze>). Second, Unity software can be downloaded from <https://unity3d.com/>, where system requirements and platform support can also be found. OpenMaze can be run on any Unity software service plan, including the *free* personal or student plan options. Lastly, a text editor equipped with a JSON linter tool (e.g., Atom, Sublime) is recommended for writing Configuration Files. Once downloaded, OpenMaze can be launched in Unity software to create a custom *experiment project*. In line with our objective of providing freely accessible software, all of the required software has free-to-access options and OpenMaze has an open access codebase.

Step 2: Environment and Stimulus Creation

Our chief objective is to provide a flexible framework that gives experimenters complete control over their navigation environments and stimuli. Accordingly, we built OpenMaze within the Unity engine to take advantage of Unity's extensive environment and stimulus creation tools. Experiment environments can be built within Unity Scenes which provide a blank canvas in which 3D models can be placed, manipulated, and arranged using a set of point-and-click/drag-

and-drop tools (Fig. 3). OpenMaze allows any number of these custom Scenes to be created and used on a trial-by-trial basis. OpenMaze does not include any models (including the ones pictured in the figures below) beyond those included in the base Unity Package. Experimenters must import their desired models using, for example, the Unity asset store, which provides a large marketplace of both free and paid assets. These models range from individual items to large-scale natural terrains and full cityscapes. If preferred, 3D models may also be imported from third-party sources with supported file types (i.e., .fbx, .dae, .3ds, .dxf, and .obj). To provide experimenters with even more options for stimuli, OpenMaze allows 2D images (e.g.,

Figure 3: *Unity Graphical User Interface*

Overview of key Unity GUI tools and features that can be used to design Scenes for an OpenMaze experiment. Hierarchy window: a list of all the objects that exist within the currently selected Scene. Scene window: allows Scenes to be created using drag-and-drop/point-and-click tools. Inspector window: displays attributes of the object currently selected in the Scene window, including Position, Rotation, and Scale. Project window: used to access all files contained within the *experiment project*. 3D models, images, and sound files can be dragged and dropped into their respective folders for use in the experiment. Game window: Used to test experiments from the participant perspective. Asset Store window: provides quick access to thousands of tools and resources (both free and paid) that can be used to create Scenes or be used as *Landmarks* and/or *Goals*. All assets depicted are part of the *Windridge City* asset package, which can be downloaded for free from the Unity Asset Store.

JPG, PNG, GIF, PICT, BMP) to either appear within the environment (e.g., to incorporate established image banks) or be shown separately as instruction screens (e.g., to present slides created in PowerPoint, Keynote, etc.).

Step 3: Create an Experiment Using the Configuration File

The OpenMaze toolbox provides the infrastructure to flexibly use Unity Scenes in experiments. Experimenters need only work with OpenMaze Configuration Files to define all the necessary parameters, obviating the need to write custom C# or JavaScript. To demonstrate the flexibility of the OpenMaze framework, we will now lead the reader through the process of creating an OpenMaze Configuration File, starting at the bottom of the experiment Hierarchy (Goals, Landmarks, and Enclosures), and then working up to Trials and Blocks.

Goals and Landmarks (Figures 4 & 5): Goals and Landmarks are objects that can be modified within Scenes on a trial-by-trial basis. Goals are interactive, collectable objects (e.g., a target in a search task), whereas Landmarks are solid, static objects (e.g., a building that only appears on some trials). Any 3D model or 2D image compatible with Unity software can be added to the appropriate project folder and used as a Goal or Landmark by defining it as such in the Configuration File. These definitions include Position, Rotation, and Scale attributes, prescribing how the stimulus is placed in a Scene. Of note, OpenMaze rotates 2D images as the participant moves to maximize their viewability and more seamlessly integrate them into a 3D setting. Additionally, the color of solid geometric shapes can be customized, and sounds can be added to Goals to signal their collection. Once defined, Goals/Landmarks can be added to a Scene by referencing their indices when defining a Trial. We review this process and provide several task examples in the Task Trials section below.

Figure 4: Goals and Landmarks Definitions

(Left) Example of Goal definition in an OpenMaze Configuration file. Each definition creates a custom instance of the objects (size, shape, colour, placement, and sound) which can be placed into a Scene. (Right) Depicts how the stimulus will be manipulated. The x, y, and z grid correspond to the Scene axis, accessible in the Unity software Scene window. Note that the Red Cube has been instantiated with a 25-degree rotation about the y-axis. Because the apple is a 2D image, it will automatically reorient to face the participant, so the rotation parameter has been excluded.

Enclosures (Figure 6): OpenMaze also provides a simple Enclosure building tool to restrict participant movement. Enclosures can be customized in several ways including: their size, number of walls (square when set to 4, pentagon when set to 5, and so on), wall height/colour, and ground pattern/colour. Additionally, an invisible Enclosure can be created by making their WallColor and/or FloorColor attributes transparent (HEX color code: “ffffff00”). Like Goals and Landmarks, Enclosures can then be added to a Scene by referencing their index number when defining Trials.

Figure 5: Goal and Landmark Placement into Scenes

(Left) Example of Landmark definition in a Configuration File. Each Landmark is defined by attribute-value pairs contained with curly brackets ({}), and index numbers are implicitly assigned according to the order in which the Landmark is defined. (Center) When an index number is included in the Landmark attribute list of a Trial definition, the Landmark is added to the Trial Scene. (Right) Visualization of the Landmarks added to the Scene when the adjacent Trial attribute-value pair appears in the Trial definition. Similarly, Goals and Enclosures can be added to Scenes by referencing their index number in the appropriate Trial attribute-value pair (see Fig. 7). All assets depicted are part of the *Windridge City* asset package, which can be downloaded for free from the Unity Asset Store.

Figure 6: *Enclosure Definition and Examples.*

(Left) Example of Enclosure definition in a Configuration File. Each Enclosure is defined by attribute-value pairs contained within curly brackets ({}). Customization is achieved using the following attributes: The Radius to dictate the size; the Sides to dictate the shape; the WallColor to dictate color of the walls; the WallHeight to dictate the height of the walls, the GroundTileSides to dictate the shape of the tiles; the GroundTileSize to dictate the size of the tiles, the GroundColor to dictate the color of the tiles; and the Position to dictate where the Enclosure will be instantiated in the Scene. (Right) Visualization of the corresponding Enclosure.

Trials (Figure 7): OpenMaze includes two types of trials: Task Trials and Instruction/Cue Trials.

Task Trials can be thought of as individual navigation tasks. Defining a Task Trial involves first prescribing the Scene that the task will take place in along with the participant's initial position and facing direction. Each Task Trial can also have a specified duration, exit key, and heads-up-display options. Lastly, Goals, Landmarks, and Enclosures can be flexibly combined according to task requirements. Goals can be entered into either the ActiveGoals, InvisibleGoals, or

InactiveGoals lists (Fig. 7). Active Goals are visible to the participant and will be collected upon collision. Once collected, an Active Goal will disappear, and the (optional) associated audio file will play. Inactive Goals are also visible, but participants pass through them without consequence. Invisible Goals are like Active Goals in that they can also be collected and associated with a sound, yet are never visible to the participant. Quotas dictating the number of Goals (Active and Invisible) that need to be collected to terminate the Task Trial can also be included. Optional Landmarks and Enclosures can be added to further customize the features of environments on a trial-by-trial basis.

While the individual components are simple, when combined they provide a great deal of task design flexibility. For example, the various types of Goals can be used to create tasks ranging from object-place learning (where Active Goals are collected during training, but Invisible Goals are used to test memory for their location), wayfinding (where Invisible Goals are placed at key locations along a route), foraging (where multiple Active/Invisible Goals must be collected), and lure discrimination (where Active Goals must be distinguished from Inactive lure objects). In parallel, Landmarks can be added, removed, and manipulated to signal different task contingencies, or test how performance depends on their inclusion. Custom 3D model mazes (e.g., T-mazes, radial mazes) can also be defined as Landmarks and added to different Scenes across Trials to generate different combinations of local and global contextual cues. Or, for open field tasks, customizable Enclosures can be added and parametrically manipulated. An added feature of using Enclosures is that the Starting Position/Facing attributes may be left empty for random initial placement within the Enclosure.

Instruction/Cue Trials present static images to the participant. Any image file that is supported by Unity software within the appropriate experiment project folder can be used. The user can set the duration for Instruction/Cue Trials as well as what input is required to proceed to the next Trial.

Figure 7: Trial Definition and Examples

(Left) Example Trial definitions. Trials are defined by attribute-value pairs contained within curly brackets (`{}`). The first example defines an Instruction/Cue Screen Trial. When called, the image file "Instruction.png" will be displayed for 3 seconds or until the spacebar is pressed, whichever comes first. The second example defines a Task Trial. When executed, the participant will be placed at the coordinates (0,0) within Scene 2. Goals 4, 5 and 6 and Landmark 1 (defined in the Goals and Landmarks section of the Configuration File) will be placed in the Scene. The Trial will terminate after 60s has elapsed, or the "x" key is pressed, or when all three Goals have been collected (Quota = 3), whichever comes first. (Right) Depiction of the corresponding Trials. All assets depicted are part of the *Windridge City* asset package, which can be downloaded for free from the Unity Asset Store.

Blocks (Figure 8): Once defined, Trials can be sequenced using experiment Blocks. Importantly, the same Trial may be included multiple times, supporting repeated learning/testing procedures. Trial presentation can be made in a serial order or be randomized with or without replacement. Several performance metrics are also tracked throughout a Block, which can be used to assess whether participants have reached any set performance criteria. Attainment of performance criteria can be evaluated either at the Block or Trial level, such that Blocks repeat (Block criteria) or Trials continue (Trial criteria) until the criteria is reached. OpenMaze also includes a C# template (described on the OpenMaze website) for those wishing to write custom functions. Finally, once *Blocks* have been defined, they are sequenced according to a BlockOrder, which allows repetition, to create a full experiment.

Figure 8: *Block Syntax and Examples*

(Left) Example of Block definitions in a Configuration File. BlockOrder sequences the execution of Blocks defined in Blocks section. Block definitions are each contained within curly brackets ({}) and include a prescribed TrialOrder that is executed serially by default (top and bottom Blocks). Alternatively, RandomlySelect and Replacement attributes can be added to randomize the Trial sequence. When these options are added, 0 acts as a place holder in the TrialOrder sequence, which will be randomly filled by the Trials specified in the lists of Orders. In the middle Block, Trial 1 will always occur first and Trial 5 will always occur last, but the remaining trials will be randomly selected from trials 2-4. The bottom Block contains performance criteria evaluated at the Trial and Block levels. Successful Trials are tabulated after each Trial and at the end

of the Block. When three successful Trials are achieved the Block will terminate. If three successful Trials have not been completed by the end of the Block, the Block will be repeated.

Step 4: Testing and Exporting an Experiment

Configuration File Testing: Experiment Configuration Files can be run directly within Unity software and tested from the participant's perspective in the Game Window (Fig. 3E).

Conveniently, during execution, environments may be manipulated in the Scene Window, with effects witnessed in real time. While specific Trials and Blocks cannot be selected for testing within a Configuration File, Configuration Files can be temporarily edited so that specific events occur at the beginning of an experiment to facilitate the process.

Building an Experiment Application: While experiments can be conducted using Unity software, this is not recommended as it is computationally expensive and requires that Unity software be installed on all testing computers. Instead, we recommend building stand-alone application files using Unity software. Conveniently, Unity supports cross-platform applications, allowing, for example, experiments created using a Windows device to be exported as a MacOS application. OpenMaze experiment applications have been extensively tested on MacOS and Windows operating systems. Unity software also supports a variety of additional build platforms including Linux, mobile (iOS, Android), and Web Graphics Library (WebGL).

By default, OpenMaze applications probe the user for a configuration file when launched. This is a convenient option for implementing multiple versions of experiments in a laboratory setting to support counterbalancing, multiple sessions, between subject manipulations, and so on, because multiple configuration files can be included in the same application. Experiment applications are also compatible with online testing; participants can download applications to run on their local

computer without the need for additional software. OpenMaze includes the optional setting (AutoRun) for applications to automatically execute a specified Configuration File to facilitate online testing. Detailed instructions on running experiments online – including using “AutoRun” – can be found in the *Online Experiments* section of the User Manual (<https://openmaze.duncanlab.org/documentation#online>).

Input Devices: By default, OpenMaze uses the arrow keys of a standard keyboard, or a single joystick, allowing participants to move forward and backward and rotate in place left or right. However, controls can be easily changed through Unity software’s Input Options to include more complex movement controls: for example, allowing up/down/left/right head motions to be controlled with the mouse (used in conjunction with a keyboard) or adding a second joystick (e.g., gamepads with two joysticks). Supported input devices include most digital (e.g., keyboards, digital controllers) or analog (e.g., joysticks, gamepads) devices supported by the local machine. While not supported by OpenMaze, Unity software is compatible with a variety of specialized devices (e.g., VR headsets, touch screens), though add-on support packages will be required for their use.

Step 5: Automated Data Collection

Each time an OpenMaze experiment is executed, output is stored in a new, uniquely named, CSV file. Output files record the participant position (x, y, and z) and viewing angle (y rotation value), Goal collisions, and keystrokes. Each row also includes the Block and Trial index, as well as a Trial sequence number identifying how many Trials have occurred in the Block. Rows are also timestamped with the absolute system time of the device running the experiment. OpenMaze records positional data each time the Unity software Update() function is called, which is once

per screen frame (dictated by the display's refresh rate). This ensures the output is synced as closely as possible to the participant's experience. Collisions with Goals are written to the output file whenever a collision is detected by the Unity software `FixedUpdate()` function, which is called every 20ms, meaning that the output file will mark the time at which a Goal was collected within 20ms.

We verified the precision and accuracy of OpenMaze event and output timing (see Supplementary Information and Supplemental Figure 1). In brief, we found that participant position was consistently recorded at the monitor's refresh rate. Using external sensors, we also verified that the times recorded for Trial onsets and Goal collisions were accurately logged with respect to the beginning of the experiment. While event timing was quite precise, we did find that loading a trial resulted in delays in the expected event times, as is common when loading complex graphics. To minimize these lags, OpenMaze uses asynchronous loading – the upcoming trial is loaded during the preceding one, which remains on the screen until the loading is complete. In our testing, this approach still left over 100ms lags in the loading of instruction screens and over 300ms lags in the loading of complex Task Trials. All timing is accurately logged so these delays do not compromise data quality. We do, however, recommend estimating total experiment times by testing an experiment as these delays will accumulate across the session. This would be especially important when using OpenMaze in functional magnetic resonance imaging (fMRI) studies, as the imaging sequence length should be set to at least the maximum expected task duration, including lags. Notably, many navigation tasks may be terminated by the participant's performance. In these cases, total task duration would be hard to estimate in advance. We recommend using arbitrarily long imaging sequences in these cases, which are then manually terminated after the task completes. Details of our timing tests and

instructions on how it can be replicated by the user can be found in the Supplementary Information.

Discussion and Future Directions

We designed OpenMaze with the objective of giving researchers with minimal programming experience the free and flexible tools that they need to build first-person VE navigation tasks from the ground up. As we reviewed above, OpenMaze achieves this vision in many ways. It leverages Unity software's powerful environment and stimulus creation tools, which are already accessible to those with minimal programming experience. And because OpenMaze uses empty template Scenes, users are free to build any environment they desire. OpenMaze's Configuration Files can then be used to construct bespoke tasks. The modular experiment components forming the lowest level of the OpenMaze hierarchy (Scenes, Goals, Landmarks, and Enclosures) can be combined in any way the experimenter desires to augment the environment, constrain participant movement, or add task functions on a trial-by-trial basis. Higher-level components – namely, Trials and Blocks – also have flexible parameters that can be used to randomize trial presentation and establish performance criteria, for example. Moreover, since experiments are defined in the human-readable JSON format, even atypical and complex designs can be constructed without any formal programming.

OpenMaze does have some limitations, however, that potential users should consider when choosing among VE experiment tools (for a comparison of OpenMaze with Landmarks and EVE, see Supplemental Figure 2). First, while learning JSON syntax is vastly simpler than writing Unity source code, some users may find the GUIs offered by alternative toolboxes, like

Landmarks and EVE, more intuitive than OpenMaze’s Configuration Files. Second, while OpenMaze offers highly flexible design possibilities within first-person navigation tasks, it does not currently support other spatial cognition tasks, like judgements of relative direction and map learning, or surveys. Researchers interested in administering a wider battery of common assessments would be better served by one of the options reviewed in our Introduction. Third, OpenMaze does not currently support VR integration and does not send or receive signals through parallel/serial ports. While these functions can be achieved with a combination of Unity software, add-on packages, and C# coding, other options, like Landmarks, EVE, and MazeSuite have out-of-the-box solutions. Notably, however, OpenMaze’s precise time logging make it a strong option for fMRI experiments, provided that (a) the system is triggered with USB input and (b) the researcher does not require trial presentation at particular, predetermined times. easily, OpenMaze does not preprocess its output data. Other software options provide trial-level summaries (e.g., time to target location and deviation from optimal route). Because OpenMaze does not assume any particular task structure, it simply provides detailed data logging in an easy-to-read CSV file but leaves it to the user to implement their custom analysis plan. While flexible, this solution may be less desirable to those who are not proficient in analysis tools, like R.

Some of these limitations reflect our prioritization of task flexibility, which occasionally comes at the cost to user accessibility. To address this concern, we provide extensive documentation and video tutorials on the OpenMaze website, <https://openmaze.duncanlab.org/>. These resources do not assume any expertise in experiment design, Unity software, or programming. They provide detailed step-by-step instruction on all of OpenMaze’s features, walking a novice user through the full experiment development path. In fact, we informally assessed the user-friendliness of OpenMaze by asking three undergraduate research assistants (RAs)—all

OpenMaze novices—to go through the video tutorials and rate their experience. Despite having only self-reported basic ($N=1$) to intermediate ($N=2$) coding knowledge and no familiarity with Unity or JSON files, the RAs rated the experience of both (a) downloading and setting up the software (mean rating = 3.66) and (b) following along with the tutorials (mean rating = 4.33) as being moderately to very easy (both on a 5-point scale ranging from *1 – Very Difficult* to *5 – Very Easy*; download and setup). RAs also indicated that they were able to create their own custom experiments after completing the video tutorials (5-point scale ranging from *1 – Strongly Disagree* to *5 – Strongly Agree*; mean=4.0). Therefore, given the extensive documentation and tutorial resources we have provided, we feel confident that researchers with varied backgrounds will be able to envision and readily implement their desired paradigms within OpenMaze.

Other current limitations reflect opportunities for future development. Indeed, building OpenMaze to work with Unity software allows for many exciting future directions. For example, Unity software can be used to build applications for a variety of platforms. Most recently, we have leveraged this function to conduct OpenMaze experiments online using web-based cloud services. We have successfully conducted hundreds of sessions in which participants download self-contained applications corresponding to their operating system and run experiments on their local machines. In future developments, we could extend officially supported systems to include mobile devices and web applications. Relatedly, while not officially integrated into the initial release, OpenMaze has been augmented by other researchers to create VR experiments (Tarder-Stoll, Baldassano, & Aly, 2020).

We are also excited to extend experiment design tools in future versions of OpenMaze. Indeed, we have several new tools under development. One supports the navigation of Scenes from an

allocentric, or bird’s eye, perspective. We have included a beta version of this functionality in our initial offering for those interested. We are also exploring the future inclusion of advanced Goal objects, such as interactive animations (e.g., treasure chests participants can open to reveal their contents). We plan to keep most of our extensions restricted to first person navigation tasks, and encourage users looking to implement other types of navigation tasks to explore other tools.

To best support our users across OpenMaze’s evolution, we will provide static documentation for our first official release (<https://github.com/DuncanLab/OpenMaze/releases/tag/v1.1.0>) and separately document our newest updates. All functionality outlined in this paper describes our first release and is documented in more detail on <https://openmaze.duncanlab.org/>. This website will remain unchanged to maintain the alignment of these two resources. Future development and maintenance of OpenMaze will be led by the first author of this paper, Kyle Alsbury-Nealy. This development will be documented on <https://OpenMaze.ca> and the corresponding codebase will be hosted at <https://github.com/OpenMaze-Experiment-Design>. We also hope that our users will see OpenMaze not as a static toolbox, but rather as a development platform. We invite those in the user community with development ideas to clone or fork OpenMaze from the GitHub development repository and create new features, which will be reviewed for inclusion in future releases. Researchers can also submit new feature requests or report on software issues through the GitHub development repository for review by the core OpenMaze development team.

We recognize that our vision for OpenMaze cannot possibly foresee the full scope of features that researchers will require, and therefore hope that through active involvement of our users OpenMaze will continue to be refined and augmented to meet the broad and diverse needs of the field. It is through this collaboration that we envision future releases of OpenMaze to include an

even wider range of first-person navigation tasks and accommodate more experimental paradigms. More broadly, we believe the increasing use of real-world, immersive environments and other ecologically valid stimuli in cognitive psychology and neuroscience research represents an important shift in the field and indicator of what is to come (Sonkusare, Breakspear, & Guo, 2019). Such approaches are necessary for understanding whether those mechanisms identified in simple, lab-based tasks indeed “scale up” to the real-world situations we truly seek to understand. Tools like OpenMaze bring us one step closer to that goal. Moreover, convincing graphics with seamless participant interaction are key for understanding abilities such as spatial navigation and memory in special populations or experimental setups with restricted physical movement; and may also make for greater engagement and increased compliance among other groups (e.g., children). As the field continues to move towards understanding human cognition across all people, in the broadest possible sense, tools such as OpenMaze will enable researchers to answer questions that are key pieces to the puzzle.

Open Practices Statement:

The source code and other materials for all the OpenMaze toolbox and timing analysis described above are available on the Duncan Lab GitHub (<https://github.com/DuncanLab>). We did not preregister any experiments.

References:

- Ayaz, H., Allen, S. L., Platek, S. M., & Onaral, B. (2008). Maze Suite 1.0: A complete set of tools to prepare, present, and analyze navigational and spatial cognitive neuroscience experiments. *Behavior Research Methods*, 40(1), 353–359. <https://doi.org/10.3758/BRM.40.1.353>
- Coughlan, G., Laczó, J., Hort, J., Miniñane, A. M., & Hornberger, M. (2018). Spatial navigation deficits — Overlooked cognitive marker for preclinical Alzheimer disease? *Nature Reviews Neurology*, 14(8), 496–506. <https://doi.org/10.1038/s41582-018-0031-x>
- De Kort, Y. A. W., Ijsselstein, W. A., Kooijman, J., & Schuurmans, Y. (2003). Virtual

- Laboratories: Comparability of Real and Virtual Environments for Environmental Psychology. *Presence: Teleoperators and Virtual Environments*, 12(4), 360–373. <https://doi.org/10.1162/105474603322391604>
- Deuker, L., Bellmund, J. L., Navarro Schröder, T., & Doeller, C. F. (2016). An Event Map of Memory Space in the Hippocampus. *ELife*, 5, 1–26. <https://doi.org/10.7554/eLife.16534>
- Deuker, L., Doeller, C. F., Fell, J., & Axmacher, N. (2014). Human Neuroimaging Studies on the Hippocampal CA3 Region – Integrating Evidence for Pattern Separation and Completion. *Frontiers in Cellular Neuroscience*, 8(March), 1–9. <https://doi.org/10.3389/fncel.2014.00064>
- Donders, F. C. (1869). On the Speed of Mental Processes. *Nederlandsch Archief Voor Genees-En Natuurk Unde*, 4, 117–145. Retrieved from papers3://publication/uuid/D3F5FF60-AC14-411C-8D58-500C241DBA84
- Ekstrom, a D., Kahana, M. J., Caplan, J. B., Fields, T. a, Isham, E. a, Newman, E. L., & Fried, I. (2003). Cellular networks underlying human spatial navigation. *Nature*, 425(6954), 184–188. <https://doi.org/10.1038/nature01955.1>
- Ekstrom, A. D., Arnold, A. E. G. F., & Iaria, G. (2014). A critical review of the allocentric spatial representation and its neural underpinnings: Toward a network-based perspective. *Frontiers in Human Neuroscience*, 8(OCT), 1–15. <https://doi.org/10.3389/fnhum.2014.00803>
- Goslin, M., & Mine, M. R. (2004). The Panda3D graphics engine. *Computer*, 37(10), 112–114. <https://doi.org/10.1109/MC.2004.180>
- Grübel, J., Weibel, R., Hao Jiang, M., Holscher, C., Hackman, D. A., & Schinazi, V. R. (2017). EVE : A Framework for Experiments. In *Spatial Cognition X* (Vol. 1, pp. 159–176). <https://doi.org/10.1007/978-3-319-68189-4>
- Hartley, T., Lever, C., Burgess, N., & O’Keefe, J. (2014, February 5). Space in the brain: How the hippocampal formation supports spatial cognition. *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol. 369. <https://doi.org/10.1098/rstb.2012.0510>
- Hecht, S., Shlaer, S., & Pirenne, M. H. (1942). Energy, quanta, and vision. *Journal of General Physiology*, 25(6), 819–840. <https://doi.org/10.1085/jgp.25.6.819>
- Herweg, N. A., & Kahana, M. J. (2018). Spatial representations in the human brain. *Frontiers in Human Neuroscience*, 12(July), 1–16. <https://doi.org/10.3389/fnhum.2018.00297>
- Jacobs, J., Weidemann, C. T., Miller, J. F., Solway, A., Burke, J. F., Wei, X. X., ... Kahana, M. J. (2013). Direct recordings of grid-like neuronal activity in human spatial navigation. *Nature Neuroscience*, 16(9), 1188–1190. <https://doi.org/10.1038/nn.3466>
- Lloyd, J., Persaud, N. V., & Powell, T. E. (2009). Equivalence of real-world and virtual-reality route learning: A pilot study. *Cyberpsychology and Behavior*. <https://doi.org/10.1089/cpb.2008.0326>
- Maguire, E. A., Burgess, N., & Keefe, J. O. (1999). Human spatial navigation: cognitive maps, sexual dimorphism and neural substrates. *Current Opinion in Neurobiology*, 9, 171–177.
- Miller, J. F., Neufang, M., Solway, A., Brandt, A., Trippel, M., Mader, I., ... Schulze-Bonhage, A. (2013). Neural Activity in Human Hippocampal Formation Reveals the Spatial Context of Retrieved Memories. *Science*, 342(6162), 1111–1114. <https://doi.org/10.1126/science.1244056>
- Nadasdy, Z., Nguyen, T. P., Török, Á., Shen, J. Y., Briggs, D. E., Modur, P. N., & Buchanan, R. J. (2017). Context-dependent spatially periodic activity in the human entorhinal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, 114(17), E3516–E3525. <https://doi.org/10.1073/pnas.1701352114>
- Serino, S., Morganti, F., Di Stefano, F., & Riva, G. (2015). Detecting early egocentric and

- allocentric impairments deficits in Alzheimer's disease: An experimental study with virtual reality. *Frontiers in Aging Neuroscience*, 7(MAY), 1–10.
<https://doi.org/10.3389/fnagi.2015.00088>
- Solway, A., & Kahana, M. J. (2014). PandaEPL: A library for programming spatial navigation experiments. *Behavior Research Methods*, 45(4), 1–27. <https://doi.org/10.3758/s13428-013-0322-5>.PandaEPL
- Sonkusare, S., Breakspear, M., & Guo, C. (2019). Naturalistic Stimuli in Neuroscience: Critically Acclaimed. *Trends in Cognitive Sciences*, 23(8), 699–714.
<https://doi.org/10.1016/j.tics.2019.05.004>
- Starrett, M. J., McAvan, A. S., Huffman, D. J., Stokes, J. D., Kyle, C. T., Smuda, D. N., ... Ekstrom, A. D. (2020). Landmarks: A solution for spatial navigation and memory experiments in virtual reality. *Behavior Research Methods*. <https://doi.org/10.3758/s13428-020-01481-6>
- Starrett, M. J., Stokes, J. D., Huffman, D. J., Ferrer, E., & Ekstrom, A. D. (2019). Learning-dependent evolution of spatial representations in large-scale virtual environments. *Journal of Experimental Psychology: Learning Memory and Cognition*, 45(3), 497–514.
<https://doi.org/10.1037/xlm0000597>
- Steemers, B., Vicente-Grabovetsky, A., Barry, C., Smulders, P., Schröder, T. N., Burgess, N., & Doeller, C. F. (2016). Hippocampal Attractor Dynamics Predict Memory-Based Decision Making. *Current Biology*, 26(13), 1750–1757. <https://doi.org/10.1016/j.cub.2016.04.063>
- Tarder-Stoll, H., Baldassano, C., & Aly, M. 2020, May. Multi-Step Prediction and Integration in Naturalistic Environments. *Poster Presented at the Cognitive Neuroscience Society Meeting*.
- Tsitsiklis, M., Miller, J., Qasim, S. E., Inman, C. S., Gross, R. E., Willie, J. R., ... Jacobs, J. (2019). Single-neuron representations of spatial memory targets in humans. *Current Biology*, 523–753. <https://doi.org/10.1101/523753>
- Tsitsiklis, M., Miller, J., Qasim, S. E., Inman, C. S., Gross, R. E., Willie, J. T., ... Jacobs, J. (2020). Single-neuron representations of spatial memory targets in humans. *Current Biology*, 30(2), 245-253.e4. <https://doi.org/10.1016/j.cub.2019.11.048>
- Tu, M.-C., & Pai, M.-C. (2006). Getting lost for the first time in patients with Alzheimer's disease. *International Psychogeriatrics*, 18(03), 567.
<https://doi.org/10.1017/S1041610206224025>
- Vasser, M., Kängsepp, M., Magomedkerimov, M., Kilvits, K., Stafinjak, V., Kivisik, T., ... Aru, J. (2017). VREX: An open-source toolbox for creating 3D virtual reality experiments. *BMC Psychology*, 5(1), 1–8. <https://doi.org/10.1186/s40359-017-0173-4>
- Weisberg, S. M., Schinazi, V. R., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2014). Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning Memory and Cognition*.
<https://doi.org/10.1037/a0035261>
- West, G. L., Konishi, K., & Bohbot, V. D. (2017). Video Games and Hippocampus-Dependent Learning. *Current Directions in Psychological Science*.
<https://doi.org/10.1177/0963721416687342>
- Wilson, P. N., Foreman, N., & Tlauka, M. (1996). Transfer of spatial information from a virtual to a real environment in physically disabled children. *Disability and Rehabilitation*.
<https://doi.org/10.3109/09638289609166328>

SUPPLEMENTARY INFORMATION

Timing Precision

To assess the precision of OpenMaze output timing, we generated three Scenes with varying graphical demands: the low demand Scene (S^L) contained a single 3D model terrain object; the medium demand Scene (S^M) contained ~500 3D models; and high demand Scene (S^H) contained ~1000 3D models. These Scenes were embedded with five Goals, five Landmarks and an Enclosure in Task Trials. The experiment application was executed on a Windows 10 machine (System Type: 64-bit Operating System; Processor: Intel® core™ i5-7300U; CPU: 2.60GHz – 2.71GHz; RAM: 8.00GB, Graphics Card: Intel® HD Graphics 620) at the highest graphics quality setting using a 60Hz screen with resolution of 3840x2160 pixels. For analyses which required external monitoring, we connected a photodiode (model GL5529) and a sound sensor (model LM393) to an external Raspberry Pi (**Supplemental Figure 1**). Experiment scripts and setup schematics can all be found on the OpenMaze timing project GitHub (<https://github.com/DuncanLab/OpenMaze-Timing>).

Supplemental Figure 1: *Timing Analysis Equipment Setup*

To externally validate the output timing, we compared output from OpenMaze CSV files to times recorded by a photodiode and sound sensor connected to a Raspberry Pi.

To assess position data output frequency, we ran a Configuration File consisting of 300, 5-second Trials divided equally across each condition. As expected, position data across all conditions were recorded at a rate of 60.76Hz (SD = 11.01). Fluctuations in timing occurred predominantly within the first 200ms of each Trial and then remained relatively stable (Trial time < 200ms: mean = 61.01Hz, SD = 32.91, min = 4.69Hz, max = 250Hz; Trial time > 200ms: mean = 60.17Hz, SD = 3.45, min = 38.46Hz, max = 142.86Hz; note the decreased SD and range for Trial time > 200ms). Graphics demands also influenced the output rate ($F(2,52367) = 63.99, p < 0.001$), with further analyses (restricted to Trial time > 200ms) revealing that Scenes with high graphical demands had a higher output rate (likely driven by higher output variability) than those with low and medium demands (S^H : mean = 60.78Hz, SD = 7.16, min = 27.78Hz, max = 111.11Hz; S^M : mean = 60Hz, SD = 2.25, min = 50Hz, max = 71.43Hz; S^L : mean = 60Hz, SD = 2.29, min = 43.48Hz, max =

90.91Hz; t-test for S^H vs. S^L : $t(23302) = 16.75, p < 0.001$; S^H vs. S^M $t(23904) = 16.935, p < 0.001$). Medium and low did not differ from each other (S^M vs. S^L : $t(10870) = 0.07, p = 0.94$). Note, though, that even the statistically significant differences have negligible effects sizes (Cohen's D : S^H vs. S^M : 0.12; S^H vs. S^L : 0.12).

We also verified the precision of Trial onset times and collision events using external sensors (Fig. S1). We used a Configuration File consisting of 120 Trials evenly divided over the three graphical demand conditions. Each Trial ended upon collecting 3 of the 5 embedded Goals. To assess Trial onset times, we used OpenMaze's Timing Test functionality. Once this attribute is added to a Configuration File, a lightbox on the bottom right corner of the screen alternates between black and white upon each Trial onset. Onset times that were externally recorded with a photodiode placed in front of this box closely tracked those recorded in the OpenMaze output file (difference score of external - OpenMaze: mean = 0ms, SD = 5.3ms, max = 14.1ms, min = -14.2ms). These timing discrepancies were not influenced by the Scene's graphical demands ($F(2,296) = 0.001, p = 0.999$). Similarly, we found only minor discrepancies between the collision timestamps recorded by OpenMaze and the corresponding sound onsets recorded by Raspberry Pi (external - OpenMaze: mean = 35.68ms, SD = 29.7ms, max = 73.43ms, min = -64.31ms), and again the discrepancies did not depend on graphical demands ($F(2,117) = 0.513, p = 0.6$). We note that these analyses provide conservative estimates because the external recordings contain some measurement error. While these results demonstrate that the timestamps in OpenMaze output are quite precise, we also provide an in-depth guide on how users can test timing on their local machines at <https://github.com/DuncanLab/OpenMaze-Timing>.

Lastly, we assessed lags in Trial presentation times, which are common when loading complex graphics. OpenMaze utilizes asynchronous loading to combat this issue: the upcoming Trial Scene is loaded during the preceding Trial, which remains on the screen until the loading is complete. To determine whether keeping the previous trial on the screen during loading extends Trial duration, we compared the recorded and prescribed (i.e., defined in the Configuration File) Trial durations. We found that Trials preceding Instruction/Cue Screen Trials (with a lower loading demand) were displayed for 132.8ms (SD = 27.12ms, max = 372ms) longer than their prescribed length, whereas Trials preceding Task Trials (with a higher loading demand) were displayed for 375.2ms (SD = 100.54ms, max = 504ms) longer. Fortunately, brief Instruction/Cue Screen Trials can be presented before each Task Trial. This would minimize the extent to which participants receive an extra—or unpredictable—amount of exposure to task-relevant stimuli. While these lags are accurately recorded in the output, their cumulative effect can extend the total experiment duration. We therefore recommend collecting timing data on the designated testing computers prior to data collection to anticipate and account for these lags.

	OpenMaze	Landmarks	EVE
User Interface			
No Coding Required	✓	✓	✓
Experiment Design Interface	JSON Configuration Files	GUI Accessible Through Unity	GUI Accessible Through Unity
Supported Operating Systems	Windows and macOS	Windows and macOS	Windows Only
Devices Support			
Keyboard/Gamepad Compatible	✓	✓	✓
VR Compatible	Requires Additional Software	✓	✓
Physiological Recording Support	✗	✓	✓
Eye Tracking Support	✗	✓	✓
Supported Tasks			
First Person Navigation	✓	✓	✓
Map Learning	✗	✓	✓
Judgment of Relative Direction (JRD)	✗	✓	✓
Alternative Forced Choice	✓	✗	✓
Multi-object Collection (foraging decision making)	✓	✗	✓
Questionnaires	✗	✗	✓
Goal/Target objects change detection	✓	✓	✓
Task Design Features			
Block level task options	✓	✓	✓
Instruction/Cue Screens	Images	Text	Text and custom input fields
Custom Instruction Presentation Order	Trial-by-Trial	Dictated by chosen task	Dictated by chosen task
Performance Criterion/Conditions	Trial & Block Level	Block/Task Segment	Block/Task Segment
Environment Manipulation	Trial-by-Trial	Block/Task Segment	Experiment Level
Custom 3D Interactive Objects	✓	✓	✓
Custom 2D Interactive Objects	✓	✗	✗
Customizable Heads-up-Display	Trial-by-Trial text/image	✗	Experiment Level text/image
Data Output			
File Type	Comma-separated values	Comma-separated values	SQL database
Preprocessed Data	✗	Distance and Direction Measurements	Distance and Direction Measurements
Data Processing Tools	✗	✗	"everttools" R-package

Supplemental Figure 2: *Feature Comparison Chart*

We limited our feature comparison to the Landmarks and EVE packages since they are most similar to OpenMaze. Landmarks and EVE features are restricted to those available to researchers through the GUI out-of-the-box, however both provide code templates for more functionality.