Videogame Design for Cognitive Enhancement through Micro-Puzzle Cognitive Profiling

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ABSTRACT

The Advanced Distributed Learning (ADL) Initiative's Next Generation Learner researchers previously investigated whether five video game design features hypothesized to be contained within Portal 2 might increase cognitive adaptability (CA). Their results highlighted a lack of understanding of the cognitive elements of video games within the literature. Subsequently, a protocol for applying cognitive task analysis (CTA) to video games was developed and a CTA was performed on Portal 2 to understand the cognitive components, decisions, and knowledge needed for successful gameplay, as well as to gain a detailed understanding of its design. As a result of the CTA, a compendium of within-level tasks and puzzles the player must complete, referred to as "micro-puzzles," was compiled, and mapped to the five design features for CA. Results from the initial study showed that certain measures of CA were increased in those playing Portal 2; however, the design of Portal 2 was treated as a "black box." Through performing a CTA, the presence of the five design characteristics for adaptability was validated by location and by micro-puzzle. Although precisely identified and mapped by game location, there were no specific alignments identified between cognitive measures and micro-puzzle attributes, or between micro-puzzle typology and design feature support. For this reason, the researchers are cognitively codifying micro-puzzles in Portal 2 by type according to their measurable cognitive attributes. This involves defining the micro-puzzles and mapping them to cognitive skills, measurable by the CANTAB battery of tests for CA, followed by empirical testing in the game environment. This paper details this codification and mapping, as well as efforts to build levels in Portal 2 based upon this information in order to cultivate specific cognitive skills, empirically validate the correlation of puzzle type in-game to cognitive gains, and further validate hypothesized game design features to improve cognitive functioning.

ABOUT THE AUTHORS

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Shenan Prestwich joined the ADL team in early 2009, and has since been a part of efforts to research and evaluate advanced technology-based/technology-mediated training, as well as the effectiveness and impact of emerging learning technologies and adaptive learning, cognition, and behavior. Shenan holds an undergraduate degree from James Madison University, and a Masters from Johns Hopkins University. Her research at ADL has explored topics such as leveraging video game design to enhance cognitive adaptability, transfer from simulation training to on-the-job performance and how to foster more effective transfer from simulation training, and the effectiveness of computer-based simulation games for learning.

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INTRODUCTION

Training for adaptability and an "adaptive stance" (Grisogono, 2010) have been a long-standing interest of the United States (U.S.) Department of Defense (DoD), commensurate with the rise of asymmetric and irregular warfare. Adaptive stance and adaptability, while an important competency at a performance level, begins on a cognitive level. That is, micro-momentary decisions and cognitive processing (i.e., adaptive cognition) are the basis for adaptable behavior and performance, which in turn comprise adaptability at a human systems level. Therefore, utmost importance must be placed upon understanding and fostering adaptability at its origin: the cognitive level.

To address the exigencies of organizations within military and industry, and the educational outcomes defined as 21st Century skills, learning environments need to support the types of activities fostering these skills in a manner that is highly engaging, motivational, leverages generational differences, ubiquitous, easily accessible, and appeals to a variety of learners and age groups. Games and serious games support both generational differences and a varied, ubiquitous set of technological opportunities that can be leveraged for learning (TRADOC, 2010). As such, if games and serious games do indeed have the ability to foster the cognitive adaptability, they could be employed more extensively as components of virtual learning environments. This thinking was the impetus for a program of research conducted by the Advanced Distributed Learning (ADL) Initiative consisting of initial research in 2012, which studied the effects of gameplay of Portal 2, a game identified as having five features hypothesized to foster cognitive adaptability (CA), on the CA of Airmen at Sheppard AFB, as measured by the CANTAB battery of tests for cognitive adaptability (Gallagher & Prestwich, 2012). Next were efforts developing a novel protocol for cognitive task analysis (CTA) on narrative, puzzle-logic video games in order to determine the presence of the five design characteristics posited to increase CA as well as to precisely map the cognitive and mechanical requirements of successful gameplay in Portal 2. Through performing a CTA, the presence of the five design characteristics for adaptability was validated by location within the game and by micro-puzzle, or smaller puzzle/task within each level.

Although precisely identified and mapped by game location, there were no specific alignments identified between cognitive measures and micro-puzzle attributes, or between micro-puzzle typology and design feature support. For this reason, the researchers are cognitively codifying micro-puzzles in Portal 2 by type according to their measurable cognitive attributes. This process has produced definitions of micro-puzzles mapped to cognitive skills as defined in the previous CTA. Through analysis of the micro-puzzles and their associated cognitive skills, the next step was to hypothetically associate them to specific executive function capabilities that are measurable by the CANTAB battery designed to test primary cognitive adaptability components. This phase culminates the initial theory-building phase of the research in preparation for empirically testing within Portal 2. This paper details the theory building phase, as well as a description of the next phase which includes building targeted levels in Portal 2 to cultivate specific cognitive skills, then empirically test puzzle type in-game interventions to measurable cognitive gains, and further validate hypothesized game design features to improve cognitive functioning.

BACKGROUND: BRAIN TRAINING AND APPLICATIONS

There is ample evidence from the literature that not only can specific cognitive functions be improved through training, but that structural changes in specific areas of the brain are linked to such training tasks and that such improved functioning on a cognitive level is broadly transferable across domains, supporting the importance of cognitive training.

Can Cognitive Functioning Be Trained?

There are a multitude of studies indicating that cognitive abilities--particularly executive functions--are not static, but can in fact be improved through certain training tasks, including those found in cognitively engaging games. Jaeggi, Buschkuehl, Jonides, & Perrig (2008) performed a study that showed increased fluid intelligence (a cognitive capacity once thought to be fixed) as a result of performing a task (dual n-back task) that challenged working memory and divided attention. Klingberg's (2010) literature review also confirms that working memory itself is not a fixed trait, but a function that can be improved with "adaptive and extended training" (Klingberg, 2010, p. 317). The dual n-back task has since been incorporated into many online brain training games that can be found easily through simple Web searches.

Many similar findings can be seen in the field of occupational therapy. Both Klingberg et al (2005) and Gibson, Gondoli, Johnson, Steeger, Dobrzenski, and Morrissey (2011) conducted studies that showed improved visual memory and response inhibition as well as primary memory function, respectively, after working memory training in children with ADHD, and Holmes, Gathercole, and Dunning (2009) showed that an adaptive training program that significantly taxed working memory resulted in improved working memory in children with low memory skills and demonstrated poor progress in reading and mathematics. Additionally, Kronenberger, Pisoni, Henning, Colson, and Hazzard (2011) showed working memory training to have positive effects on both verbal and non-verbal working memory in children with cochlear implants. At the opposite end of the age spectrum, Willis et al's (2006) study of older adults (with an average age of 73.6 years, an age group particularly vulnerable to cognitive decline) showed significant improvements in verbal episodic memory, inductive reasoning, and processing speed that continued for five years after the initiation of the intervention designed to train each of the aforementioned faculties. Similarly, cognitive remediation therapy (CRT), a neurocognitive psychotherapy technique aimed at improving three distinct executive functions--cognitive flexibility, working memory, and planning (Delahunty & Morice, 1993; Delahunty, Reeder, Wykes, Newton, & Morice, 1999)---has been shown overwhelmingly in the literature to have positive results in improving its three target cognitive areas (McGurk, Twamley, Sitzer, McHugo, & Mueser, 2007) in populations with typically sub-normal functioning, including those with schizophrenia or traumatic brain damage.

Additionally, the world of video games and "brain-training" games has shown promising results for the ability of games to positively impact cognitive abilities. A 2003 study by Green and Bavelier showed that gamers performed better than non-gamers in measures of visual attention, and that the visual attention of non-gamers increased after playing action video games. Similarly, Gallagher and Prestwich (2012) found that even 12 hours of mostly consecutive play of Portal 2, a puzzle-logic game by Valve™, can result in increased focused attention as compared to levels before gameplay, and that those who reported playing video games for 19 or more hours a week scored higher in measures of spatial working memory, spatial sequencing, and cognitive planning. Additionally, Lumosity, a popular suite of online games that claims to improve cognitive functioning by training seven core cognitive capabilities, has been the subject of a variety of studies that has shown that playing Lumosity's brain-training games for 20 minutes a day, five days a week, resulted in improved working memory, visual attention, and executive function (Hardy & Scanlon, 2009; Scanlon, Drescher, & Sarkar, 2006, 2007a, 2007b).

It has also been shown in a familiar study underwritten by the British Broadcasting Company (BBC) that online brain training games do not produce any effect. The interventions in the study consisted of reasoning games for one group and non-reasoning games for another with a control group simply doing online look-up activities. Benchmark testing for transference consisted of four types of cognitive tests - measures of reasoning, verbal short-term memory, spatial working memory and paired-associates learning (Owen, Hampshire, Grahn, Stenton, Dajani, Burns, & Ballard2010). However, this study has been discussed as methodologically flawed in many ways. For example, the sample could be considered biased and not representative or well matched to the testing methods. Also, the intervention time was only a total of four hours over a period of six weeks, and the benchmark tests were not comprehensive or sensitive enough to potential changes that may have occurred over time. Simply put, the BBC study is not seen as detracting from the promise of cognitive training through gaming (Zelinski, 2010; Garwood, 2012).

Structural Neuroplasticity and Training Tasks

In addition to functional outcomes, cognitive training tasks have also been shown to correlate actual physical changes to the structure of the brain, implying a plasticity to not only the brain's capabilities, but its organic formation. Klingberg (2010), cited previously, found that, in addition improvements in working memory capacity itself, working memory training is associated with changes in brain activity in the frontal and parietal cortices and basal ganglia, as well as changes in dopamine receptor density. Olsen, Westerberg, and Klingberg (2004) also found increased levels of activation in the parietal cortex as well as the prefrontal cortex in ADHD-diagnosed children following working memory training.

Perhaps most interesting, however, are the structural changes seen in the brain following activities and learning situations that occur in real-world, everyday situations. Maguire et al (2000) studied London cab drivers, a population famed for their extensive training and knowledge of how to navigate between a myriad of locations in the city, a skillset colloquially known as being "on The Knowledge." Analyzing the structure of the hippocampi, a part of the brain associated with memory, of taxi drivers versus non-taxi drivers via structural MRI, Maguire, et al found that the posterior hippocampus was larger in taxis drivers than non-taxi drivers, and that hippocampal volume correlated to amount of time spent as a taxi driver (Maguire et al, 2000). Draganski, Gaser, Busch, Schuierer, Bogdahn, and May (2004) found similar hippocampal changes in medical students. Even what are traditionally thought of as "leisure activities" can have structural impact on the brain; Draganski et al (2006) found changes in brain structure related to visual processing as subjects in their study learned to juggle, and Haier, Karama, Leyba, and Jung (2009) found that cortical thickness and activation levels in some brain areas increased in subjects after playing Tetris.

Transfer of Cognitive Gains Across Domains

Beyond the obvious benefit of improvement of the specific cognitive skills being trained, one of the aspects of functional and structural neuroplasticity that makes cognitive training such an important tool to leverage when evaluating the potential of games for learning is its transferability across domains. There is a host of evidence for this in the field of working memory training for children with ADHD. Not only did working memory capacities improve in these studies after training tasks designed specifically to strengthen working memory, but also children saw improvements in math reasoning performance (Holmes et al, 2009), word reading and reading comprehension (Dahlin, 2011), executive functioning (Beck, Hason, Puffenberger, Benninger, & Benninger, 2010), non-trained visuo-spatial working memory tasks, and performance on Raven's Progressive Matrices (a nonverbal complex reasoning task) (Klingberg, Forssberg, & Westerberg, 2002), as well as reduction of off-task behavior (Green et al, 2012), excess motor activity during tests (Klingberg et al, 2002), and inattention and hyperactivity/impulsivity (Klingberg et al, 2005). Additionally, both Ball et al (2002) and Willis et al's (2006) studies show that brain training in the fields of memory, reasoning, and speed of processing in older adults (aged 65 or older) resulted in slower declines in related, but not directly trained, instrumental activities of daily living.

Finally, Hertzog, Kramer, Wilson, and Lindenberger's (2009) review concludes that structured experiences in situations that demand an executive coordination of skills, such as complex video game environments or situations demanding task-switching or divided attention, train a strategic control over one's cognition that shows transfer to different task environments.

COGNITIVE PROFILING OF PORTAL 2 MICRO-PUZZLES

As it is apparent, then, that cognitive functioning can be trained and improved, in ways both functional and structural, and that such improvements are highly transferable, the question then becomes, how can video games--and more specifically, video game design--be leveraged to do this?

A study performed by ADL in 2012 drew on literature from cognitive and clinical psychology surrounding the meta-competency of CA to posit five game design characteristics thought to increase CA in players: implicit rules, implicit shifting of rule sets, dynamic shifting environments, implicit reinforcement for actions and decisions to reach a final goal, and some degree of open-endedness in gameplay. Portal 2, a puzzle-logic game produced by Valve™ software, was identified as possessing these five traits (a sixth trait, time-based constraints, was added to the list of traits for cognitive adaptability after the study was conducted), and was used to test the effects of 12 consecutive hours of gameplay by Airmen at Sheppard Air Force Base of such a videogame on cognitive adaptability. This was measured by the CANTAB battery of tests for cognitive adaptability, developed jointly by Cambridge Cognition an ADL. Table 1, below, describes each test in the battery and the cognitive components involved in each.

Table 1. CANTAB Battery of Tests for Cognitive Adaptability

CANTAB Test	Definition/Cognitive Components
AST = attention switching	Switching attention between two qualities/attributes and ignoring task-irrelevant information in the face of interfering/distracting event
SSP = spatial span	Recall of sequencing as a function of placement in space
SWM = spatial working memory	Retaining spatial information and manipulating remembered items in working memory via heuristic strategy
RVI = rapid visual information processing	Sustained attention
OTS = one-touch stockings of Cambridge (executive planning)	Spatial planning, visualizing solution without acting, planning actions and understanding their consequences
RTI = reaction time	Time taken to react to stimuli; includes both movement time and response latency

The study showed positive results for focused attention (both signal detection and response latency) in the group playing Portal 2, as well as positive results (measured by a survey documenting gaming experience) for spatial working memory, spatial sequencing, and executive planning--all four of them components of CA--for those who played video games in general for 19 or more hours a week (Gallagher & Prestwich, 2012). An example of one of the CANTAB tests is provided below in Figure 1.

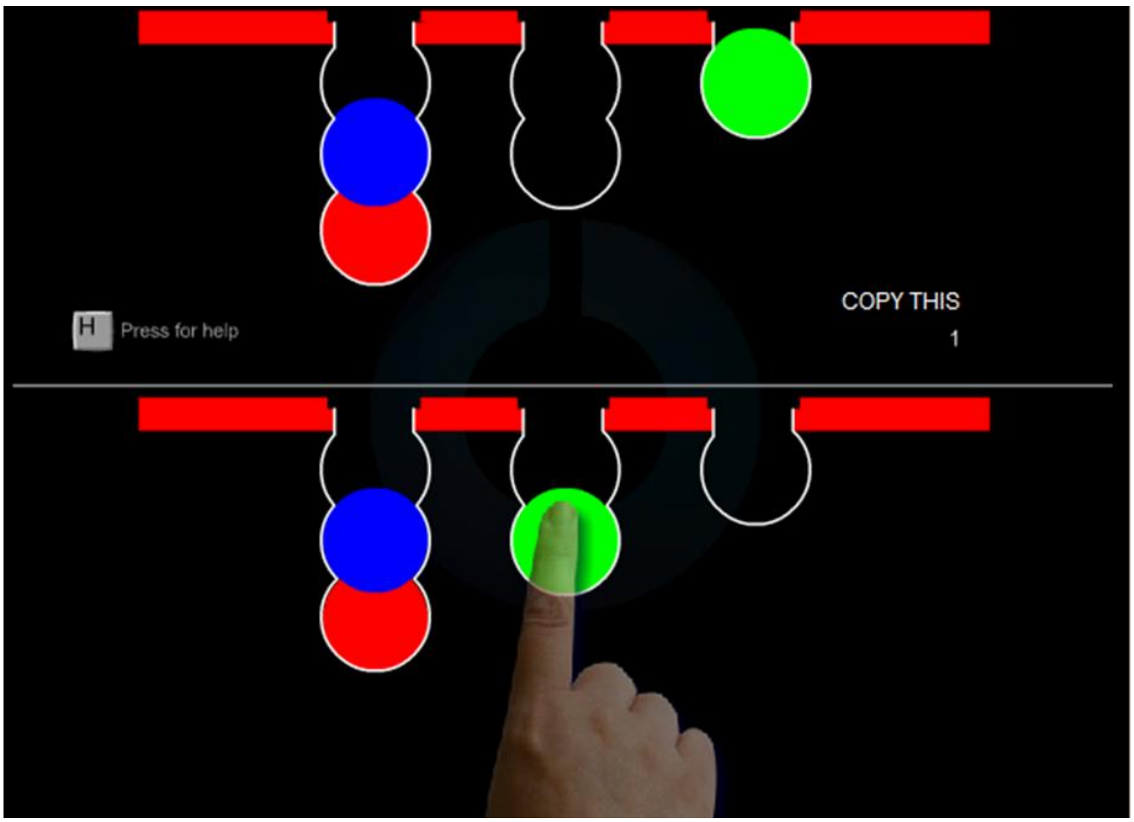

Figure 1. Example of the CANTAB test for executive planning - One Touch Stockings (OTS) of Cambridge (Cambridge Cognition Limited, 2011).

To deepen the understanding of game design and its role in cognitive adaptability as employed in Portal 2, a novel protocol for cognitive task analysis (CTA) on narrative, puzzle-logic video games was developed and performed. The goal in doing so was to determine the presence of the five design characteristics posited to increase CA as well as to precisely map the cognitive and mechanical requirements of successful gameplay in Portal 2. Through performing a

CTA, the presence of the five design characteristics for adaptability was validated by location within the game and by micro-puzzle, or smaller puzzle/task within each level. Examples of micro-puzzles include tasks such as “catching objects in mid-air,” “use of lasers through emancipation grills,” and “utilization of momentum.” It’s important to note that the difference between a micro-puzzle and a mere obstacle in the game is whether or not it presents a problem to the gamer. Nothing becomes a puzzle until it becomes a problem. For instance, in Portal 2, if the gamers finds themselves trapped in a room in which they know immediately they will need to use portals to escape from, it is not a micro-puzzle, as they know what needs to be done, with what tools, and how to use those tools. If, on the other hand, they encounter a tool they have never used before and need to induce how to use it in order to solve a problem, that object’s function is a micro-puzzle within the larger context of the puzzle. A puzzle may contain more than one micro-puzzle or different combinations of micro-puzzles.

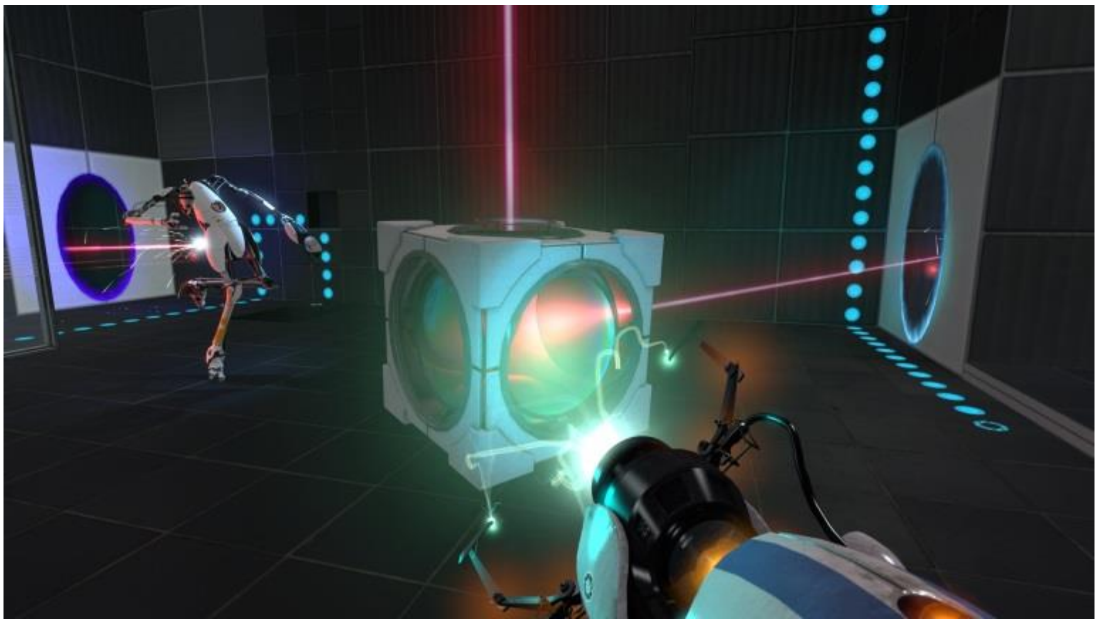

Figure 2. A Player Utilizing Tools and Environmental Features In Solving Micro-Puzzles to Solve the Larger Puzzle of the Level

Though precisely identified and mapped by game location, there were no specific alignments identified between cognitive measures and micro-puzzle attributes, or between micro-puzzle typology and design feature support. It was for this reason that ADL researchers began efforts to create a “cognitive profile” of each micro-puzzle, defining it by type and mapping that type (and by extension, each micro-puzzle) to a specific cognitive function, or functions (as measurable by the CANTAB battery) hypothesized to be enhanced or be engaged in the player and to produce transference to other abstract measures of specific cognitive capabilities. They also began to map each micro-puzzle type to the design features for cognitive adaptability--the five outlined in the previous study at Sheppard AFB. As micro-puzzles are the building blocks of the overall narrative of each level, and it is within these micro-puzzles that the player is forced to engage cognitively with the game, it is important to understand how these features that presumably link to cognitive adaptability present themselves within the puzzle structure of the game. It is also important to understand how levels can be optimally designed to enhance the specific desired cognitive capabilities.

In examining the various micro-puzzles identified within the game and classifying them by type, the researchers leveraged prior knowledge gained through the CTA to analyze what characteristics defined each, including what types of manual or cognitive action they required from the player, as well as the type of interactions (between player and environment, player and object, object and environment, object and object, or other combinations) inherent in the micro-puzzle. This activity led to the following micro-puzzle types and definitions:

- **Function:** Player has to induce the function of a tool or object in the game whose function is not explicitly revealed.
  - Ex: Inducing that the function of the round, black, circular object on the wall (the "laser catchers," though not explicitly called so in the game) is to initiate some change in the environment, e.g., opening a door or raising a staircase from the floor, when activated by direct contact with a laser.
- **Feature-Function:** Player has to induce the function of a specific (often newly-introduced) feature of a tool or object in the game whose function is not explicitly revealed.
  - Ex: Inducing that the different sides of a reflection cube determine the direction a laser is redirected in when pointed at the cube.
- **Usage:** Player has to induce the ways in which an object, tool, or concept (e.g., laws of gravity or momentum) can be used to accomplish a task or goal (i.e., induce the intended or a beneficial interaction between player and object or concept).
  - Ex: Inducing how to use the spring-loaded faith plates in order to propel the player to reach a certain space in the environment.
- **Relationship:** Player has to induce the nature of a relationship between two or more objects, tools, or environmental features (i.e., how two or more things interact, and the nature of their interaction). This is often intertwined with solving a usage micro-puzzle.
  - Ex: Inducing the relationship between a laser catcher and a laser, i.e., that the round object on a wall called a laser catcher is activated via contact with a laser beam, an interaction that then induces various changes in the environment.
- **Action:** Player has to induce how to take a particular action.
  - Ex: Inducing how to make the player's avatar in the game catch an object in mid-air.
- **Sequence of Action:** Player has to induce the proper sequence of actions needed to be taken in order to achieve a goal.
  - Ex: Player has to induce the correct order to press buttons in order to activate portals to travel from location to location.
- **Timing:** Player has incorporated the element of timing into their execution of an action in order for it to be successful in furthering their accomplishment of a goal or task.
  - Ex: Player has to push a pedestal button to make a box drop into a portal, then push a second button at the correct moment as it comes out the other end to make a wall raise up momentarily from the floor, in order to stop the box's momentum and keep it from falling into the water (so that the player may then use it).
- **Rule Induction:** Player has to induce a rule not explicitly given.
  - Ex: Player has to induce that only one reflection cube can ever be present at a time in a given environment (and that if a second cube is introduced, the first one disintegrates).

Based on the cognitive demands of the identified micro-puzzles, the researchers developed a mapping from each type of micro-puzzle to a potential set of measurable cognitive capabilities from the CANTAB battery. Each type of micro-puzzle is seen as exercising a defined set of cognitive skills; however, in most cases the measurable outcomes from the battery produced a one-to-many relationship in the mapping. This may present difficulty in defining specific causality based upon battery component as most of the battery is specifically targeted toward measuring components of executive function, while to accomplish most cognitive activities, more than one tested component are required. However, if possible, through factoring and other methods, the researchers will clarify the variables as much as possible. For the purposes of this research it may be that a high level of granularity may not be necessary.

Table 2, below, shows how each micro-puzzle type was mapped to CANTAB cognitive adaptability battery tests and CA design features.

Table 2. Mapping of Micro-Puzzle Types to CANTAB Tests and CA Design Features

Micro-Puzzle Type	Definition	Hypothe-sized CANAB Test(s)	Design Feature Exemplified*
Function or Function-Change	Determining properties of an object ("thing," noun, etc) that define its nature and determine how it interacts with the surrounding world.	AST, SWM	1, 2, 3
Feature-Function or Feature-Function Change	Determining the function of specific features of an object (as opposed to the object as a whole).	AST	1, 2, 3
Relationship	Determining how one or more objects function or can function in relation to each other, including the outcome of interaction between one or more objects.	AST, SWM, OTS	1, 2, 3
Sequence of Action	Determining the sequence of mechanical and/or cognitive steps that must be executed in order to achieve a goal.	SWM, SSP, OTS	4, 5
Action	Determining how to perform an individual action (e.g., jumping, picking up objects).	OTS, SWM	1, 2, 4, 5
Usage	Determining how to use/interact with an object according to one or more of its intended or incidental functions.	AST, SWM, OTS	1, 2, 4, 5
Timing	Executing an action in accordance with the specific timing required in order to achieve a goal.	RTI, RVI, OTS	6
Rule Induction	Inducing implicitly presented rules from environmental/circumstantial clues.	AST, OTS	1, 2, 3

*Design Features

1. Implicit rules and rule sets
2. Implicit shifting of rules and rule sets
3. Dynamic, shifting environments
4. Implicit reinforcement for individual actions and decisions to achieve a final goal
5. Open-endedness

NEXT PHASE AND FUTURE RESEARCH

Identifying the typologies of micro-puzzles present within Portal 2 and hypothesizing their mapping to cognitive skills is only the first step in realizing the goals behind this cognitive profiling effort. In order to determine if the hypothesized cognitive qualities associated with these micro-puzzle typologies can actually be positively affected through a player's engagement with those particular types of micro-puzzles, associations between micro-puzzle type and cognitive outcomes must be investigated and established. If possible, using empirical testing, causality may also be determined at the level of the battery components or component types – i.e. executive function and attention.

For the next phase, researchers plan to use Valve™ software's open source Portal 2 Level Editor to build custom levels using basic building blocks of the game's elements. Level development starts with a basic environment or "room" in the game that is altered to build out the environment of the level as well as add any object present in any part of the original Portal game, with the ultimate goal of each level being to exit the room. Custom levels will be built that are comprised of specific and similarly designed types of micro-puzzles profiling each level combined into a "chapter" to increase specific measurable cognitive capabilities. Each level/chapter will be targeted to increase a particular cognitive capability – i.e. cognitive flexibility as tested by the AST. The effect of the micro-puzzles on a player's cognitive function will then be tested after a certain amount of gameplay using the CANTAB battery, with the hope that by controlling for game design to eliminate as many extraneous design or narrative features other than the micro-puzzle types in question, their effects on cognition in the context of gameplay can be isolated and identified. To begin to target specific battery components, an iterative design-research approach will be used tailoring micro-puzzles/levels to produce maximum targeted gains. As essentially a design partner, the CANTAB battery is not optimal for measure of transference but as a design standard. To investigate true transference, future research will incorporate online braining training tasks and/or other online of computer-based cognitive measures.

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