Chapter 2
Measuring Problem Solving Skills in Portal 2

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This chapter describes current research investigating the use of the video game Portal 2 (Valve Corporation) as a vehicle to assess and potentially support problem solving skills in students. Portal 2 is an example of a well-designed game in that it provides players with a very rich, interesting environment whereby players interact with complex problems, encounter adaptive challenges, receive ongoing feedback, and engage in meaningful learning (Gee 2003; Shute et al. 2011). As Van Eck (2007) has argued, playing games is an important part of the human experience, and serves as the basis for experiential learning. However, as we progress through life, playing-to-learn decreases, particularly in formal educational settings.

A main reason why this research on assessing and supporting problem solving skills is important is because in today's interconnected world, being able to solve complex problems is, and will continue to be, of great importance. However, students today are not receiving adequate practice solving such problems. Instead, they are exposed to problems that tend to be sterile and flat in classrooms and experimental settings (e.g., math word problems, Tower of Hanoi). We believe that schools need to move beyond the simple content-learning mindset and towards assessing and supporting important skills in the twenty-first century.

A survey conducted by the *Global Strategy Group* (a leading American research firm) has suggested that college graduates today are not prepared for their future careers (as cited in Minners 2012). Participants included 500 elite business decision makers selected by the researchers. Nearly half (49 %) of them agreed that having strong problem-solving skills is the most important skill set they are looking for in job applicants. But schools are falling short of supplying students with these skills. One problem is that learning and succeeding in a complex and dynamic world is not easily or optimally measured by traditional types of assessment (e.g., multiple-choice

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responses, self-report surveys). Instead, we need to re-think assessment, identifying skills relevant for the twenty-first century—such as complex problem solving—and then figuring out how best to assess students' acquisition of the skills. Valid assessments are key to providing effective support.

Our research was aimed at answering three questions:

1. Will students in either our experimental (Portal 2) or comparison condition (Lumosity) show significant improvement on their problem-solving skills after playing their assigned game for 8 h?
2. Will the Portal 2 group show equivalent gains on problem-solving skill compared to the Lumosity group?
3. Will the in-game measures of problem-solving skill (particular to each gaming condition) predict players' outcome measures?

The organization of our chapter is as follows. We begin with a brief review of the literature on problem-solving skill. Next, we discuss the advantages of using stealth assessment in games. This is followed by our study design and outcome measures. We then present the results from our study to answer our research questions, and conclude with ideas for future research in the area.

2.1 Literature Review

2.1.1 Problem-Solving Ability

Problem solving has been studied extensively by researchers for decades (e.g., Gagné 1959; Jonassen 2003; Newell and Shaw 1958). It is generally defined as "any goal-directed sequence of cognitive operations" (Anderson 1980, p. 257) and is regarded as one of the most important cognitive skills in any profession as well as in everyday life (Jonassen 2003). There are several characteristics of problem solving as identified by Mayer and Wittrock (1996): (a) it is a cognitive process; (b) it is goal directed; and (c) the complexity (and hence difficulty) of the problem depends on one's current knowledge and skills.

Can problem-solving skills be improved with practice? Polya (1945) has argued that problem solving is not an innate skill, but rather something that can be developed. Students are not born with problem-solving skills. Instead, these skills are cultivated when students have opportunities to solve problems. Researchers have long argued that a central point of education should be to teach people to become better problem solvers (Anderson 1980). And the development of problem-solving ability has often been regarded as a primary goal of the education process (Ruscio and Amabile 1999). But there is a gap between problems in formal education versus those that exist in real life. Jonassen (2000) noted that the problems students encounter in school are mostly well-defined, which contrasts with real-world problems that tend to be messy, with multiple solutions possible. Moreover, many problem-solving strategies that are taught in school entail a "cookbook" type of memorization, resulting in functional fixedness, which can obstruct students' ability to solve problems for which they have not been specifically trained. Additionally, this pedagogy can also stunt students' epistemological development, preventing them from developing their own knowledge-seeking skills (Jonassen et al. 2004). This is where good digital games (e.g., Portal 2) come in—which have a set of goals and complicated scenarios that require the player to generate new knowledge.

Recent research suggests that problem-solving skills involve two facets: rule identification and rule application (Schweizer et al. 2013; Westenberg et al. 2012). "Rules" in problem solving refer to the principles that govern the procedures, the conduct, or the actions in a problem-solving context. Rule identification is the ability to acquire knowledge of the problem-solving environment; and rule application is the ability to control the environment by applying that knowledge. In our current research, we did not directly collect data on students' rule identification skill as that typically involves paper-and-pencil tests or think-aloud protocols, which would disrupt students' gameplay. However, since rule application is the outward expression of one's rule identification, the measurement of rule application will reflect students' ability to identify rules.

Complex problems usually combine a mixture of basic rules and rules that require cognitive flexibility–the ability to adjust prior thoughts or beliefs and explore alternative strategies in response to changes in the environment (Miyake et al. 2000). Any given problem in Portal 2 requires the application of either basic rules or rules that require cognitive flexibility. Cognitive flexibility is the opposite of functional fixedness, defined as the difficulty that a person experiences when attempting to think about and use objects (or strategies) in unconventional ways (Duncker 1945). Such cognitive rigidity causes people to view a particular type of problem as having one specific kind of solution without allowing for alternative strategies and explanations (Anderson 1983).

Researchers (e.g., Gee 2007; Van Eck 2006) have argued that playing well-designed video games can promote problem-solving skills because of the requirement for constant interaction between the player and the game, usually in the context of solving many interesting and progressively more difficult problems. However, empirical research examining the effects of video games on problem-solving skills is still sparse. Our research intends to begin to fill this gap. Below is the internal structure of problem-solving skills that guided our research (Fig. 2.1).

2.1.2 Materials

Portal 2 is a popular linear, first-person puzzle-platform video game developed and published by Valve Corporation. The official age rating for the game is 12 or above but it is a fun brain teasing game that has wide appeal to players of all ages. Players take a first-person role in the game and explore and interact with the environment. The goal of Portal 2 is to get to an exit door by using a series

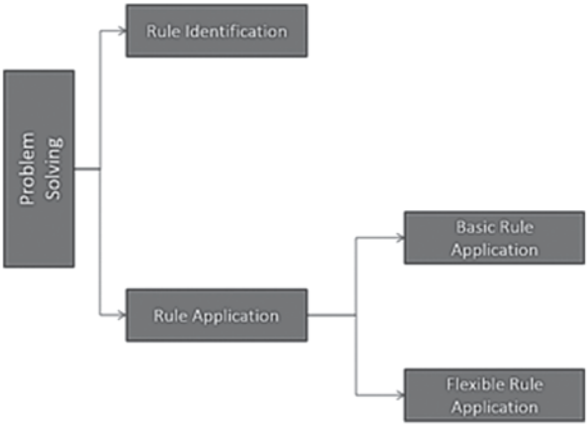

Fig. 2.1 Internal structure of problem solving skill

of tools. The primary game mechanic in Portal 2 is the portal gun, which is a device that can create inter-spatial portals between two flat planes. Puzzles must be solved by teleporting the player's character and various objects using the portal gun. To solve the progressively more difficult challenges, players must figure out how to locate, obtain, and then combine various objects effectively to open doors and navigate through the environment to get to the exit door. In addition to resources in the game that can help in the quest, there are also various dangers to avoid–such as turrets (which shoot deadly lasers), and acid pools. All of these game elements can help (or hinder) the player from reaching the exit.

The initial tutorial levels in Portal 2 guide the player through the general movement controls and illustrate how to interact with the environment. A player can withstand some amount of damage but will die after sustained injury. There is no penalty for falling onto a solid surface, but falling into a bottomless pit or a toxic pool will kill the player immediately.

Portal 2 provides a unique environment that can potentially promote problem-solving skills through providing players extensive practice figuring out solutions to complex problems on their own. In Portal 2, upper levels usually require skills or knowledge that players acquire from prior gameplay. This will push them to activate or examine their existing schemas. We believe that problem-solving skills learned in Portal 2 can be transferred beyond the immediate game environment. In 1989, Chi, Lewis, Reimann, and Glaser found out that successful students monitor their own learning process and generate explanations while studying. They could refine and expand the conditions in the examples given and apply the general knowledge learned from the examples toward problem solving in new contexts. Bransford and Stein (1984) also argued that people are able to apply information to a broad range of tasks if they learn with understanding.

Figure 2.2 illustrates how "flinging" works in Portal 2. That is, if a player jumps down to an entrance-portal (see arrow 1), he will be teleported through the inter-portal space and fly out of the exit-portal (arrow 2). The momentum he accumulates

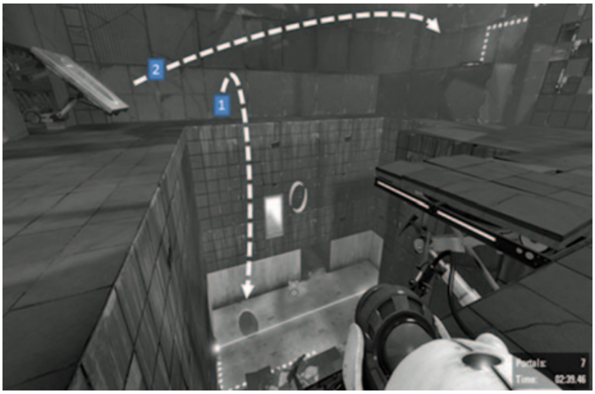

Fig. 2.2 Flinging in Portal 2

during the free fall will be conserved, and will provide sufficient energy to launch him over to the higher platform located across the plate where the exit-portal is placed. In another level, the player may have to use an in-game device called a “faith plate” which bounces objects (including players) upward upon contact to create momentum for the fling. Other tools that are available later in the game include redirection cubes, repulsion gel, propulsion gel, conversion gel, hard light bridges, funnels, and so on. Players need to learn the basic rules about each tool and then apply the tools as applicable. To succeed in later levels, a player will sometimes need to apply a tool in a different way from how it was learned. For instance, in early levels, players learn that the blue (repulsion) gel can be used to enable bouncing in the game. Later, the player needs to flexibly apply this rule by using the blue gel to smother turrets rather than using it for bouncing. This is important since the way in which students learn problem-solving strategies may influence their subsequent ability to understand and flexibly apply this information in the world.

We identified and used 62 levels in Portal 2 that elicit specific evidence related to problem solving skill. Basic and flexible rule application load on different levels with varying weights. For instance, a level may be easy on basic rule application, but difficult on flexible rule application. Below are examples of how the game elicits evidence for the two facets of rule application.

- Basic rule application: Basic rules in Portal 2 are rules directly instructed or that can be picked up easily. For example, players should be able to learn that the river is hazardous from the cueing picture on the floor near the river. Or, if a player fails to notice the picture and falls into the river, he will die and resurrect from the last automatic saving point. Afterwards, he should be aware of the rule. Other basic rules relate to avoiding laser beams, knocking over turrets to terminate them, and putting a cube on the weighted button to activate any device connected to it.
- *Flexible rule application*: Flexible rules in Portal 2 refer to rules that can only be inferred from the basic rules. For example, one basic rule is that the weighted button can be activated by the weight of a cube. A level following the one that instructs this basic rule requires players to realize that the body weight of the

player may be a replacement when a cube is not available. Other flexible rules in the game include the use of the hard light bridge to catch a falling cube or to hold it above a destination (e.g., a weighted button to be pressed) and release it after a sequence of actions are performed.

Lumosity, the game selected as the control condition, is a web-based platform that hosts more than 50 small-scale games. Advertisements for Lumosity note that the games were designed by neuroscientists to improve brain health and cognitive performance. The games were designed to appeal to a broad range of individuals, from kids to adults, although the website only allows persons over 13 years old to apply for an account. Most of the games focus on supporting the following skills: problem solving, cognitive flexibility, memory, attention, and processing speed. The challenge level of a game is usually decided by the presence and amount of distraction, the time limit, the salience or complexity of the pattern or rule to be recognized, and hence the amount of cognitive effort and skill required.

The Lumosity website also claims that their games provide personalized training to different users, and that 10 h of Lumosity training creates drastic improvements in problem solving, memory, attention, and mental flexibility. Choosing Lumosity as our control condition is thus a very conservative design decision.

Figure 2.3 presents how the "brain performance index" (BPI; the major indicator of players' overall performance) is calculated in the game. The BPI is the average score of speed, memory, attention, flexibility, and problem solving. Figure 2.4 is a sample game on Lumosity.com called "Word Bubbles Rising." It was designed to evaluate and enhance cognitive flexibility. Players are required to come up with as many words that contain the provided letter stems as possible.

2.1.3 Game-Based Stealth Assessment

Assessments can be deficient or invalid if the tasks or problems are not engaging, meaningful, or contextualized. This calls for more authentic and engaging assessments, which has motivated our recent research in relation to weaving assessments directly and invisibly within good games. In contrast, the amount of engagement in traditional (e.g., paper-and-pencil, multiple-choice) assessments is negligible. Another downside of traditional assessments (particularly those that are high stakes) is that they often invoke test anxiety, which can be a major source of construct-irrelevant variance. When these problems associated with traditional assessment—inauthentic and decontextualized items, and provoking anxiety—are removed (e.g., by using a game as the assessment vehicle), then the assessment should be more engaging. When assessment is seamlessly embedded within the gaming or learning environment that learners do not realize they are being assessed, we call it stealth assessment (Shute 2011). Additionally, if the assessment is designed properly, such as by using an evidence-centered design approach (Mislevy et al. 2003), then the validity argument is built directly into the assessment.

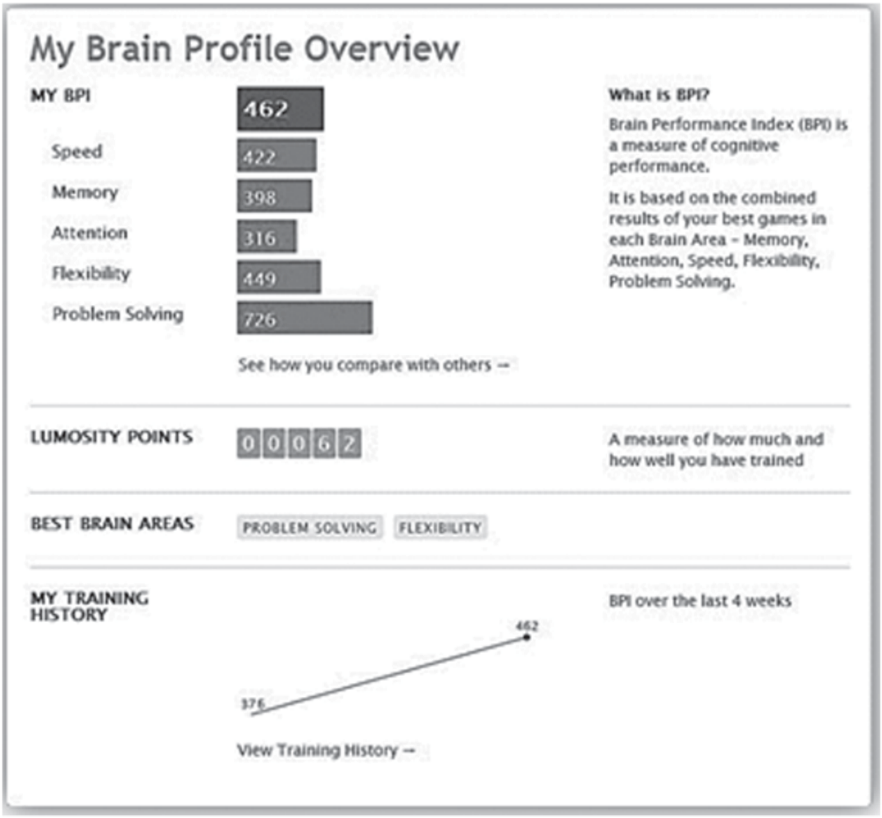

Fig. 2.3 Calculation of scores in Lumosity

Fig. 2.4 Sample game from Lumosity supporting cognitive flexibility

Using games as assessment vehicles has its own sets of issues. For instance, there are potential sources of error variance in video-game assessments such as a person's particular level of interest in the game. However, we believe this will not be a problem with Portal 2 given its broad appeal (e.g., over 3 million copies have been sold since it came out in 2012, according to GameFront). In short, we believe that Portal 2 can be used to effectively assess problem solving by virtue of having authentic, contextualized, and engaging tasks. That is, in Portal 2, if a player follows basic rules directly instructed or implied in the game such as avoiding harmful objects (e.g., turrets and acid river), or making use of the tools and other objects in the environment (e.g., refraction cubes and light bridges), this provides evidence that the player is competent at basic rule application. The players' competency levels will primarily be measured by the number of levels successfully completed over the course of 8 h of gameplay. Additional performance measures include the number of portals shot in the game, and the average time spent solving the levels (each negatively related to problem solving skill).

2.2 Method

2.2.1 Participants

Participants for our study were solicited with flyers posted throughout a university located in northern Florida. Potential participants were screened using an online video game questionnaire. A total of 218 students ages 18—22 applied to participate, and 159 were approved to participate. Among the approved population: 77 completed the study, 54 never signed up for scheduling, 1 signed up but never showed up, and 27 dropped out of the study due to various reasons (e.g., sickness or lack of time or interest). Approval was not given if a person indicated (a) susceptibility to motion sickness, (b) had played through Portal 2 before, or (c) self-reported as a frequent video game player (i.e., playing every day). Among the 77 college students who completed the study, 42 of them were randomly assigned to the Portal 2 condition and 35 were randomly assigned to Lumosity condition. About 43 % of them were male students and 57 % were females. Students were compensated with a $ 100 gift card for full participation (i.e., 8 h of gameplay and 2 h of pretests and posttests—our external measures).

2.2.2 Procedures

Consent forms were obtained from all participants before the study and then participants were randomly assigned to either the experimental group that played Portal 2, or the control group that played Lumosity. The participants were asked to come to a laboratory in the university across four sessions spanning 1–2 weeks for a total of

10 h. At the beginning of the first session, they were required to complete the online pretests (50–60 min). After they finished, they started to play their assigned game. The first three sessions lasted 3 h each. The fourth session lasted about 50–60 min where students completed the posttests. Students played their assigned game for about 8 h in total. They were provided with a pair of Sony headphones to wear during gameplay. Talking about their respective games was not permitted. One or two graduate students served as proctors in the study, per session. Proctors were instructed to only provide technical assistance to the students and to remind them to focus on the task if they appear to disengage.

2.2.3 Assessment in Portal 2

Log files that record students' performance during gameplay were extracted by enabling the developer console of the game. Students' problem-solving performance can be assessed by information in the log files. For this study, we focused on three main performance measures: overall number of levels completed, number of portals shot, and average time per level–where the last two were reverse keyed. Students' performance on these in-game measures were used to predict performance on the external measures of problem solving.

2.2.4 External Outcome Measures

The stealth assessment of students' problem-solving skills were validated against external measures of problem solving. Two sub-facets of rule application (i.e., basic rule application and cognitive flexibility) were measured. Basic rule application was measured by *Raven's Standard Progressive Matrices* (1941). The test requires participants to infer the pattern of the missing piece from the given pattern(s). Although the test is widely used as an intelligence test (e.g., Prince et al. 1996; Rushton and Jensen 2005), as Raven (2000) pointed out, Raven's Progressive Matrices focus on two components of general cognitive ability–eductive and reproductive ability. Eductive ability involves making meaning out of confusion and generating high-level schema to handle complexity. Reproductive ability is the ability to recall and reproduce information. In Portal 2, for example, players are instructed that the laser beam is deadly. If the player knows this rule, she should realize that the turret is also harmful since it emits a laser beam. We selected 12 items from the Raven's Progressive Matrices test for the pretest and 12 matched (by difficulty) items for the posttest. Each item had a time limit of 4 min before the system moved to the next item.

Cognitive flexibility was measured by two tests: insight problems and the remote association test. *Insight problems* are intended to yield an "Aha" moment for problem solvers when the solution occurs after a short or long moment of confusion (Chu and MacGregor 2011). Insight problems require individuals to shift their

Table 2.1 Descriptive statistics for Portal 2 (*n*=42) and Lumosity (*n*=35)

Measures	Portal 2		Lumosity	
	M	*SD*	*M*	*SD*
Raven's pretest	8.39	2.29	8.24	2.31
Raven's posttest	8.51	2.33	7.65	2.60
Insight pretest	1.30	0.97	1.40	1.09
Insight posttest	1.36	0.91	0.96	0.99
RAT pretest	2.59	1.40	2.65	1.28
RAT posttest	2.83	1.34	2.56	1.33
Pretest (standardized average)	−0.01	0.71	0.13	0.77
Posttest (standardized average)	0.15	0.61	−0.18	0.67

perspective and look at obscure features of the available resources or to think of different ways to make use of an object. We selected three insight problems for the pretest and three for the posttest. For instance: *You need to throw a ping-pong ball so that it will travel a short distance, come to a dead stop and then reverse itself. You are not allowed to bounce it off any surface or tie anything to it. How do you throw the ball?* The answer is to throw the ping-pong ball straight up. The question is not particularly hard, but it requires problem solvers to break from routine thinking and think beyond the immediate context. The posttest was an alternative form of the pretest. The time limit per item was 5 minutes.

The Remote Association test was originally developed by Mednick (1962) to test creative thought without any demand on prior knowledge. Each item consists of three words and problem solvers are required to find the solution word associated with all words that appear to be unrelated. The fourth word can be associated with each of the three words in multiple forms, such as synonymy, formation of a compound word, or semantic association (Chermahini et al. 2012). For example, the answer to the triad night/wrist/stop is "watch." Schooler and Melcher (1995) reported that problem solvers' success on this test correlates with their success on classic insight problems. We selected five items for the pretest and five for the posttest. The time limit for each item was five minutes.

2.3 Results

Table 2.1 displays the descriptive statistics for the external measures of problem-solving skill (based on raw scores per test—one item equals one point) for both groups.

Hypothesis 1 Players in both conditions will show improved pretest-to-posttest gains relative to the problem solving test scores. To test hypothesis 1, we computed paired t-tests, separately by condition, across the three tests (pretest and posttest data). For both the Portal 2 and the Lumosity conditions, there were no significant

Table 2.2 Posttest partial correlations to Portal 2 and Lumosity performance controlling for respective pretest scores

Measures	Portal 2			Lumosity	
	Levels completed	Portals shot	Avg level time	Problem solving	Flexibility
Raven's	0.03	−0.02	0.05	0.05	0.22
Insight	0.35*	−0.40*	−0.35*	−0.08	0.25
RAT	0.14	−0.15	−0.19	0.14	−0.01

For "levels completed," more is better; for "portals" and "level time," less is better
*$p<0.05$

differences among any of the three pretest-posttest pairs. Note, however, that for the Portal 2 condition, the three posttest scores are all higher than the pretest scores, while for the Lumosity condition, the posttests are all lower than the respective pretests.

Hypothesis 2 Students in the Portal 2 group will show comparable (or better) problem solving improvement compared to the Lumosity group. To test this hypothesis, we standardized the individual pretest and posttest scores and computed an average pretest and posttest problem solving score, per condition. Next, we computed an ANCOVA with the average posttest score as the dependent variable, by condition, controlling for pretest score. We found a significant difference in the outcome favoring the Portal 2 group: $F(1, 71)=5.49$; $p=0.02$; Cohen's $d=0.59$. To further test the hypothesis, we computed three ANCOVA tests (with corresponding pretests as covariates) to examine the effects of the two gaming conditions on the three specific tests of problem solving skill. The ANCOVA tests did not show any significant differences by condition for RAT or Raven's Progressive Matrices, but the insight posttest scores were significantly higher for the Portal 2 group compared with Lumosity group at the one-tailed level: $F(1, 66)=3.76$, $p<0.05$.

Hypothesis 3 Players' performance during gameplay will predict their posttest scores. To test this hypothesis, we correlated the performance measures associated with each condition with individual posttest scores, holding the associated pretests constant. Players' performance during gameplay was represented by three variables for the *Portal 2* group: number of levels completed (more is better), average number of portal shots in each level (less is better), and average time per level (less is better). For players in the Lumosity condition, their performance was reported in the game as "problem solving" and "flexibility" scores (other variables reported by Lumosity include memory, attention, speed, and average "brain power index"). As presented in Table 2.2, all three Portal 2 in-game measures significantly correlated with the insight posttest after controlling for pretest score. Neither of the Lumosity in-game measures correlated with players' posttest scores on any of the three external problem solving tests.

Although it was not one of the main research questions, we were curious about how much subjects in each condition enjoyed their games. We examined students' responses to a self-report question administered after 8 h of gameplay. The question was, "I enjoyed playing…" then either "Portal 2" or "Lumosity" was presented, depending on assigned condition. Students rated their enjoyment on a 1 (strongly disagree) to 5 (strongly agree) Likert scale. Those in the *Portal 2* group reported much higher enjoyment compared with those assigned to the *Lumosity* group. For *Portal 2* participants, enjoyment $M = 4.32$; $SD = 0.93$, while for the Lumosity participants, $M = 3.50$; $SD = 1.05$. The difference between the two groups' enjoyment is significant, with a strong advantage for the *Portal 2* group: $F(1, 73) = 12.69$; $p < 0.001$. Cohen's $d = 0.83$, which is a large effect size.

2.4 Discussion

Lumosity is a commercial, online suite of games that has been expressly designed by a group of neuroscientists to enhance a number of cognitive skills including problem solving and flexibility. Thus using Lumosity as our control condition was a very conservative decision, and any findings showing a Portal 2 advantage would be more powerful than using either a no-treatment control or a casual game.

When examining the results related to hypothesis 1 (i.e., pre- to posttest gains on each of the individual problem solving tests, separately by condition), we found that neither group significantly improved on any of the three external tests. The Portal 2 group, however, did show increases from pretest to posttest while the Lumosity group did not (see Table 2.1). One reason for the finding may be that students suffered from fatigue. They were asked to come to the lab four times within two weeks and they needed to stay for 3 h in three of the four sessions. Moreover, since we also investigated other skills (i.e., spatial ability and conscientiousness) in the same study, we had a large number of test items that took participants about an hour on average to finish, which may have negatively influenced participants' performance on the posttests.

Our second hypothesis examined how the participants in Portal 2 fared relative to those in Lumosity in terms of their overall and specific problem solving test scores. The composite problem solving posttest score for those playing Portal 2 (holding composite pretest score constant) was significantly higher than the posttest scores of Lumosity participants. Looking at the individual test data, we see that this was likely a function of differential performance on the insight problems test. That is, while Portal 2 players showed an increase from pretest to posttest, Lumosity players showed a decrease from pretest to posttest. This may be because Portal 2 required players to exercise insight during the solution of various problems while Lumosity did not, or at least not to the same extent.

Finally, our third hypothesis related to in-game measures of problem-solving in the Portal 2 condition. Two of the three in-game measures were significantly correlated with the insight problems. We were not surprised with this finding because Portal 2 is a video game that depends heavily on players' ability to shift their perspectives and use rules in uncommon ways, which aligns with the nature of the external test. However, we only had 3 insight problems in each form, which might be inadequate to detect any real differences in the participants. Another issue with insight problems is that some participants may have seen some of the items before. Finally, other researchers have pointed out that the skills used to solve one insight problem may not be transferrable to other insight problems. Thus to complement the insight test, we additionally used the remote association test. But one downside of this test is that it appears to require adequate language skills (specifically vocabulary) to succeed. We did not survey whether subjects were native English speakers, but the proctors did report that between 25 and 40% had accents. Thus language skills may have confounded the results.

Overall, we believe that Portal 2 has the potential to serve as a highly engaging way to measure and possibly support cognitive skills such as problem solving. A next step of this research will be to explicitly test the transferability of the gained problem-solving skills to real life situations. Given that Lumosity is a game specifically designed to improve problem-solving skills, we expected that it would support players' growth across the 8 h of gameplay. However, we did not see any improvement of problem solving skill. Furthermore, Lumosity's specific in-game measures of problem solving and flexibility did not correlate with any of our three external measures. For these reasons, we would recommend Portal 2 over Lumosity to anyone wanting to practice, in an enjoyable way, their problem-solving skills.

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