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Discovering the laws of physics with a serious game in kindergarten

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A B S T R A C T

Serious games have unique strengths that can be used to augment science education. For the current study, we developed and investigated a serious game to assess kindergartners' discovery of the laws of physics in the so-called Hippo app. The participants were 71 children, aged 5 years and 5 months on average. The app consisted of three game-plays: slides, seesaw, and pendulum. Children were asked to set variables (such as the steepness of the slide) correctly in order to provide a hungry hippo with a drink or some food. Children's gaming behavior was assessed via exploration and efficiency scores, and next related to executive control, nonverbal reasoning, and vocabulary. Exploration was defined as the number of actions corrected for the total playing time, efficiency as the number of correctly solved problems corrected for the total number of attempts. The results revealed that efficiency and exploration scores did not correlate significantly, indicating two distinct types of gaming behaviors. Both types were associated with attentional control. Mediation analysis showed that the relation between exploration and attentional control was mediated by vocabulary, while the relation between efficiency and attentional control was mediated by nonverbal reasoning. To conclude, kindergartners' efficiency and exploration can be seen as independent game behaviors; both demanding attentional control, but mediated by verbal skills in the case of exploration and by nonverbal reasoning in the case of efficiency.

1. Introduction

Scientific thinking has become more relevant in recent years. Many countries aim to stimulate scientific thinking via science education in order train future researchers, but also to make children think critically (Osborne, 2013). Serious games may very well be a supportive tool in this respect (Hamari, Koivisto, & Sarsa, 2014; Morris, Croker, Zimmerman, Gill, & Romig, 2013), and they also allow the assessment of *how* children play them. As a case in point, a physics game may help identify exactly how young children discover scientific concepts. In kindergarten, there is already some knowledge of physics (Inhelder & Piaget, 1958), but little is known about how children gain this knowledge, and how individual differences can be explained. In a game-like assessment, children would require explorative and efficient behavior. Exploration is about where to look, while efficiency is about understanding what is seen (Klahr & Dunbar, 1988). Both exploration and efficiency have been

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shown to foster scientific thinking, but which factors underlie these effects is largely unknown, especially in young children (see Legare, 2014 for a review). To identify the basis of exploration and efficiency, both cognitive (executive control, reasoning ability), and linguistic (vocabulary) factors may play a role (Wagensveld, Kleemans, Segers, & Verhoeven, 2015). In the present study, we therefore assessed individual differences in exploration and efficiency during physics gaming in kindergarten.

1.1. Serious games to enhance scientific thinking

To participate in our contemporary knowledge-based society, a broad set of skills and abilities are required, such as scientific thinking (Dede, 2010). Scientific thinking consists of scientific reasoning, i.e. domain-general skills, and scientific knowledge, i.e. domain-specific knowledge (Klahr, Zimmerman, & Jirout, 2011). Scientific reasoning is the intentional seeking of knowledge using the scientific method (Kuhn, 2004). The three components of scientific reasoning are: hypothesis generation, designing and conducting experiments, and evaluating the evidence (Klahr, 2000). These three components allow people to evaluate the validity of science-related claims, and to generate new knowledge (Fischer et al., 2014), which helps them to become critical and autonomic thinkers. To support the development of these skills, scientific activities are being undertaken in schools (e.g., Lorch, Lorch, Freer, Dunlap, & Hodell, 2014). Children can acquire scientific knowledge about specific domains via these scientific activities. An example is learning why objects float or sink (Hardy, Jonen, Möller, & Stern, 2006). Children can acquire this domain-specific knowledge via exploration and efficiency (Klahr & Dunbar, 1988). Via exploration, children can identify what the factors are that determine the effect, such as whether a boat will float. Via efficient behavior, children can generate a desired effect, such as designing a boat that will float. These types of behavior underlie scientific thinking (Legare, 2014).

A recent approach to scientific thinking in education is the use of serious games. Games provide a rich learning environment and allow children to select their own choices, which strengthens their motivation (Morris et al., 2013). The richness of serious games motivates children to process multiple, possibly interacting variables, which makes them especially suitable for science education (Morris et al., 2013). Just as rule discovery and induction are inherent to scientific thinking (Dunbar & Klahr, 2012), so are they to gaming (Greenfield et al., 1994). The richness of serious games also provides an opportunity for exploration, as there is more vigorous and prolonged exploration of stimuli that can be described as complex (Berlyne, 1966). Another advantage of serious games is that they can be regarded as ongoing assessments, providing players with the opportunity to show what they have learned (Morris et al., 2013). Learning is not linear, but multiple strategies coexist to solve a problem, which is affected by experience (Siegler, 2000), which seems to be the case in serious games as well. Therefore, serious games seem an ideal tool to assess children's explorative behavior and problem-solving skills within science education.

1.2. Discovering the laws of physics

In kindergarten, children already show the ability to think scientifically, which is about scientific reasoning and scientific knowledge. Kindergartners can reason scientifically, although they have great difficulty with hypothesis generation (Piekny & Maehler, 2013). However, many kindergartners are able to set variables correctly in order to investigate one of them. While performance decreased when the number of variables increased, many kindergartners turned out to be able to design multivariable experiments in a study by Van der Graaf, Segers, and Verhoeven (2015). It has also been shown that kindergartners can evaluate various types of evidence (Piekny & Maehler, 2013) which indicates that they have the ability to obtain domain-specific scientific knowledge themselves. Indeed, young children already show considerable conceptual change in the domain of physics, with or even without instruction (Vosniadou, 2002). In classic experiments, it has been shown that many young children understand some physics, such as the effect of the angle of a slope on how far a ball will roll (Inhelder & Piaget, 1958). They also understand how weight affects the balance of a balance beam, although they find it difficult to identify distance to the fulcrum as a variable (Inhelder & Piaget, 1958; Siegler, 1976). Using a pendulum, young children can find correspondences between the length of the string and the frequency of the oscillations, but they do not grasp the mechanism of the pendulum completely, because they fail to distinguish between their own actions and the motion of the pendulum itself (Inhelder & Piaget, 1958).

In discovering the laws of physics, exploration is needed, as well as a certain level of efficiency in problem solving. Exploration is needed to identify variables and their effects, while efficiency is needed to solve problems in a goal-directed manner. These skills have been described by Klahr and Dunbar (1988) within scientific thinking as: "The successful scientist, like the successful explorer, must master two related skills: knowing where to look and understanding what is seen" (p. 2). The first skill, exploration, involves the design of experimental and observational methods, and the second skill, efficiency, involves the formation and evaluation of theory (Klahr & Dunbar, 1988). Exploration helps children in making their prior beliefs more explicit, and there is more exploration when evidence contradicts their prior belief than when evidence confirms their prior belief (Bonawitz, Van Schijndel, Friel, & Schulz, 2012). It has also been suggested that exploration is especially relevant for young children, because of its relation to curiosity (Cecil, Gray, Thornburg, & Ispa, 1985).

Efficiency can be defined as the ability to solve as much problems in as few possible attempts. Within scientific thinking, efficient behavior would imply that one has understood the underlying mechanisms via which a certain scientific phenomenon works, because one can use it more or less instantly to solve a problem. It has been shown that when children are provided with an explanation, they can recognize information as evidence by incorporating it into a causal framework