INTRODUCTION

Emerging technologies offer learners the ability to use three-dimensional (3D) virtual environments for learning. Computer-based systems that support 3D visualization, simulation, navigation, and interaction with a 3D virtual environment have given users various virtual reality (VR) applications such as virtual prototyping, training simulators, and digital museums (Vince, 1998). The synthetic worlds created by VR can improve learners’ acquisition of theoretical knowledge...
based on their interactive and individual learning with dynamic multimedia content (Bricken & Byrnes, 1993; Poland, LaVelle & Nichol, 2003; Schmid, 1999). Unlike VR, augmented reality (AR) superimposes virtual objects on a real scene (Azuma, 1997; Milgram & Kishino, 1994; Wellner, Mackay & Gold, 1993). One feature of AR is that it adds scene-linked information to make users’ experiences more meaningful and it increases their understanding of the subject (Feiner, MacIntyre & Seligmann, 1993; Klopfer, Squire & Jenkins, 2002; Navab, 2004; Sharma & Molineros, 1997). Another feature is tangible interaction that provides users with an intuitive way of interacting with virtual objects (Poupyrev, Tan, Billinghurst, Kato, Regenbrecht & Tetsutani, 2002; Rekimoto, 1998; Ullmer & Ishii, 1997). Most AR applications using the latter feature enable users to interact with virtual objects through common physical objects such as tiles and paddles with no need for specific devices to directly manipulate the virtual objects (Kato, Billinghurst, Poupyrev, Imamoto, & Tachibana, 2000; Lee, Nelles, Billinghurst & Kim, 2004; Regenbrecht, Baratoff, & Wagner, 2001; Waldner, Hauber, Zauner, Haller & Billinghurst, 2006).

Multimedia systems have provided learners with new ways of interacting with various audiovisual resources. In molecular biology and biochemistry, up-to-date research results can be viewed through high-quality graphics that have been prepared using visualization tools. However, we think that multimedia and printed materials have been used as totally different media in distinct learning environments, each with their own advantages, where learners can only experience learning independently of one another. An AR interface has the potential to bridge the gap between multimedia and printed materials by superimposing multimedia information onto printed media. We believe that the seamless connections between virtual and real worlds can improve interactivity by creating a tangible environment that enables virtual objects to be manipulated with the physical objects that correspond to them. The basic idea is the same as that in MagicBook, which consists of a transitional AR interface that uses a real book to seamlessly transfer users from reality to virtuality (Billinghurst, Kato & Poupyrev, 2001).

Many AR systems have been developed for demonstrations, with some applications having targeted education. An AR system explaining the Earth-Sun relationship shows seasonal transitions in light and temperature by enabling the virtual Sun and Earth to be physically manipulated with handheld plates that orient their positions to the viewing perspective of the learner (Shelton & Hedley, 2002). Construct3D, a 3D geometric construction tool for teaching mathematics and geometry, provides a basic set of functions for constructing primitive forms (Kaufmann, 2002). Augmented Chemistry is a virtual chemistry laboratory in which users view simple atoms and build complex molecules according to subatomic rules (Fjeld, Juchli & Voegtli, 2003). Another molecular-biology viewer augments physical models with molecular properties such as electrostatics, which are produced by computer auto-fabrication (“3D printing”) (Gillet, Sanner, Stoffler, Goodsell & Olson, 2004). Even though a number of AR applications have been developed as demonstrations, we think that there has not really been a consensus on the effectiveness of AR within educational contexts.

An empirical study on AR-based applications for a car-door assembly revealed that the performance of tasks depended on the degree of difficulty in assembly and that AR conditions were more suitable for difficult tasks than manual conditions printed on paper (Wiedenmaier, Oehme, Schmidt & Luczak, 2003). In their performance tests, however, it took longer periods of time to complete the assembly tasks in the AR conditions than in the conditions under the supervision of an expert. Experiments related to geometry education found no clear advantages for AR-based geometry
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