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The cognitive benefits of dynamic representations in the acquisition of spatial navigation skills

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ABSTRACT

A representational theory of the mind suggests that human experiences and activities are underpinned by mental representations. This abstract task representation paradigm may explain a cognitive benefit of dynamic instructional visualisations over static alternative in the acquisition of novel procedural motor skills. In this sequel work, we explore and extend this view through empirical investigations of novel skill acquisitions in a separate but related domain of spatial navigation. We compare the post-learning virtual maze navigational performance of sixty novel learners across two groups. After controlling for spatial orientation ability and prior video gaming experience, participants that learned the task using dynamic instructional visualisations recorded significantly better performance measures than those in the static group. Additionally, within-group comparisons also show that the beneficial advantage of dynamic instructional visualisations over statics remained consistent across different task complexities. These findings provide further evidence to support the view that dynamic instructional visualisations afford more efficient transfer of novel procedural skills through computer based training than static visualisations. This has implications for instructional design especially when rapid novel situational awareness is desired such as in briefings for emergency firefighting or tactical military operations.

1. Introduction

1.1. Visualisations and instructional delivery

Effective training is essential to the acquisition of mission-critical skills in many organisations and contexts. As a result of this, organisations commit a substantial portion of their annual budget to training and personnel development processes. The Australian Government for instance spent AU$906 million for apprenticeship training subsidies in 2008/09[1]. The efficiency of any training curricula however is to a large extent dependent on the effectiveness of its instructional design and delivery components. This association between the composition of the instruction and the effectiveness of the skill/knowledge transfer has been highlighted in several training reviews (Day, Blair, Daniels, Kligyte, & Mumford, 2006). Traditionally, the instructional delivery component of the training process has been class room and text oriented. However, recent rapid advances in computing technology have made computer based multimedia instructional delivery method a more attractive option (Ahmadi, Abdolmaleki, & Khoshbakht, 2011; Rahimi & Hosseini, 2011; Wasfy, Wasfy, & Noor, 2004). The advent of modern and powerful computing devices has made it relatively easier to use multimedia components like videos, animations and still images to describe the desirable knowledge and skills to be acquired in the training process. In fact, the use of computer-based instructions has become so widespread as to have become alternative standards to traditional methods in some training aspects such as the Advance Cardiac Life Support (ACLS) component in medical training (Platz, Liteplo, Hurwitz, & Hwang, 2011). However, the effectiveness of these multimedia components for instructional design remains controversial (Watson, Butterfield, Curran, & Craig, 2010).

Of particular interest to the work reported in this paper is the debate on the cognitive benefit of dynamic versus static visualisations in the instructional interface. Dynamic visualisations are usually visual-spatial representations, such as computer animations or videos, which portray the transitory states involved in skilful task performances. Static visualisations are also visual-spatial representations but can only depict fixed spatial orientations of object/component movements. A meta-analysis of previous researches on the comparative benefits of using these different visualisations components in instructions remains largely inconclusive (Höffler & Leutner, 2007). In the review of relevant literature, Akinlofa, Holt, and Elyan (2013) reported that a benefit of static instruction visualisations was observed for largely declarative knowledge, which requires little physical manifestation of the acquired skills (Cohen

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[1] http://www.minedu.govt.nz/NZEducation/EducationPolicies/TertiaryEducation/PolicyAndStrategy/ReviewIndustryTraining/SystemsOtherCountries.aspx.

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& Hegarty, 2007; Yang, Andre & Greenbowe, 2003). On the other hand, dynamic visualisations appear to be beneficial for the acquisition of novel procedural skills involving overt physical manifestations such as skilled motor movements for mechanical assembling (Arguel & Jamet, 2009; Schwan & Riempp, 2004). This paper therefore further explores the earlier hypothesis of Akinlofa et al. (2013) that the knowledge domain of interest is a key factor for determining the effectiveness of static versus dynamic instructions for novel skill acquisitions, through comparative analysis of performance in a specific domain. This view is notably consistent with Höffler and Leutner (2007), which identifies the type of acquired knowledge as a moderator variable for the effectiveness of instruction visualisations and defined 3 levels of this variable as declarative, problem-solving and procedural-motor. Furthermore, we consider that a fundamental understanding of cognitive knowledge representations and the processing involved in instruction based skill acquisitions is essential to the comparative analysis of the benefit of dynamic over static visualisations. Therefore, we will start our discussion with a review of the representational theory of mental imagery and perception.

1.2. Mental representations in domain-specific cognitive task processing

The representational theory of mind proposes that our experiences and activities are underpinned by mental representations (Chandrasekaran, Banerjee, Kurup, & Lele, 2011). The exact nature of these representations is still subject to debate but a widely received view is the mental imagery theory (Kosslyn, 2005; Kosslyn & Pomerantz, 1977; Kosslyn, Shephard, & Thompson, 2007; Pylyshyn, 2002). Importantly, the mental imagery theory distinguishes between perception and mental imagery. Perceptual representations require external stimuli, but mental imagery refers to representations that exists or persists in the absence or after the removal of the stimuli. The mental imagery theory is particularly well developed with respect to visual perception and visual mental imagery. A core component of the theory is the retinotopical similarity in the neuro-architecture for visual perception and visual mental imagery, which has also been established in other related neuroscience research (Fox, Miezin, Allman, Van Essen, & Raichle, 1987; Fox et al., 1986; Tootell, Silverman, Switkes, & De Valois, 1982; Yang, Heeger, & Seidemann, 2007). In the mental imagery theory, this neuro-architectural similarity is defined through the visual buffer component. During visual perception, the visual buffer is thought to encode the object (shape, texture and colour) and spatial properties of the stimulus. Visual mental imagery however is the result of an 'unpacking' process through which a mental representation akin to the original visual stimulus is sequentially reconstructed in the visual buffer. An attention-shifting mechanism evident in visual perception is also active in visual mental imagery through which retrievals from long-term memory are sequentially integrated for the reconstruction of the mental image (Kosslyn, 2005).

Consistent with the mental imagery theory, Akinlofa et al. (2013) proposed a novel hybrid model as depicted in Fig. 1, which integrates modal and amodal paradigms of the cognitive processing that underpins the acquisition of novel procedural skills.

This model suggests that an abstract mental referent (*mental task model*) is created as part of the cognitive processing involved in procedural skill acquisitions. More importantly though, the model shows that the abstract mental referent is the resultant of an integral process within working memory that involves all external percept. With respect to the visual percept, this paper proposes an extension of the imagery theory with the addition of a third *motion* component to the visual buffer to explain the comparative benefit of dynamic instructional visualisations over static components in the acquisition of such procedural skills. Dynamic visualisations afford stimuli that can intrinsically encode transitory information inherent in the external percept. This intrinsic information is encoded through the *motion* component of the expanded visual buffer as well as in long-term memory. The additional information encoded through the *motion* component arguably improves the fidelity of the subsequent mental referent resultant of the 'unpacking' process in sequential mental imagery reconstruction, thus accounting for the improved task performances associated with the dynamic instructional components.

The benefit of dynamic over static visualisations in the cognitive processing associated with learning has also been found to be domain-specific and independent of the learner's expertise, provided the current learning task is novel (Akinlofa, Holt, & Elyan, 2012a). Furthermore, the role of dynamic instructional visualisations in the low-level, intertwined cognitive processing involved in novel motor skill acquisitions and its implications for post-learning task performance as been modelled computationally using the Adaptive Control of Thought – Rational (ACT-R; see Anderson et al., 2004) cognitive architecture (Akinlofa, Holt, & Elyan, 2012b). In the study reported in this paper, we explore further the reported cognitive benefit of dynamic over static instructional visualisations for the acquisition of novel procedural motor skills (Akinlofa et al., 2013; Watson et al., 2010). We do this by validating the cognitive learning model through empirical investigations in a separate, but related domain of the acquisition of novel spatial navigational skills.

1.3. Sequential representations in spatial navigation

Traditionally, spatial navigational planning has been defined as a multi-level problem solving process (Holscher, Tenbrink, & Wiener, 2011; Timpf & Kuhn, 2003; Zhang, 2008). The relevant cognitive level components of this process include perceptual scanning, knowledge-based retrievals and memory-based decisions (Reitter & Lebiere, 2010). In viewing spatial navigation as a sequential process, we consider the memory-based decision making process as the core of the model as shown in Fig. 2.

Visually perceived information is integrated with knowledge-based retrievals in this core component to determine executive actions in the resolution of navigational problems. From a cognitive architecture perspective, spatial knowledge representations have been modelled with different abstract structures including algebraic framework (Banerjee & Chandrasekaran, 2010), multi-dimensional arrays (Glasgow, 1998; Lathrop & Laird, 2007) and multi-layered hierarchies of spatial/object properties (Kosslyn, 2005). Conceptually however, acquired spatial knowledge is thought to exist either as survey way-planning or sequential route representations (McNamara & Shelton, 2003; Thorndyke & Hayes-Roth, 1982). The survey representation is an allocentric, map-like view of spatially laid out landmarks organised within a common reference system. The route representation on the other hand is egocentric and consists of sequentially organised spatial locations encoded along with respective action objects, which are executed in support of a navigational task.

Within the context of the acquisition of novel spatial navigational skills, previous studies have established an association between the initial learning perspective and spatial knowledge representations. The effect of this association on subsequent navigational performance is however still subject to debate (see Denis, 2008; Pazzaglia & Taylor, 2007; Shelton & McNamara, 2004). The acquisition of novel navigational skills may be viewed as a sequential process in general, where spatial knowledge representations of the task environment are developed incrementally as the learner interacts with the instructions. This sequential view of spatial knowledge acquisition is consistent with the neuroscience research of brain structures that support navigational performance.