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One Step At a Time: Multimodal Interfaces and Children's Executive Functioning

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Abstract — **The following study outlines a new computerized executive function task (Slippy's Adventure) inspired by the Towers of Hanoi task. The main focus was to determine if the task was developmentally sensitive. A further consideration was how physical embodiment would affect performance. This line of enquiry arose from recent developments in HCI (human computer interaction), in particular, multimodal interfaces. To investigate the role of embodiment children completed Slippy's Adventure using an electronic floor mat and a computer keyboard. The results supported our hypothesis that 7 year olds would outperform 5 year olds. However, physical action did not have an ameliorative effect on performance as predicted. The implications of these findings are discussed with future applications suggested.**

Index Terms— Developmental psychology, embodied cognition, executive function

I INTRODUCTION

Children of this generation are said to be digital natives because they are brought up in an environment filled with mobile and internet enabled devices [1]. Videogame technology in particular has grown in popularity among the younger generations. In 2013 an Ofcom report stated that 57% of three to four year olds in the UK play video games, on a range of digital devices [2]. Recently, researchers have reported that videogame interaction benefits to certain cognitive skills [3]. As such, this study used videogame technology as a tool to investigate children's cognition, specifically executive functioning (EF). An added consideration of the study was to investigate the role of movement to children's cognition using multimodal interfaces. Multimodal interfaces are devices that facilitate human-like verbal and non-verbal communication behavior (e.g. gesture and touch) [4]. As these devices continue to grow in sophistication, the actions that the user can perform could be viewed as *embodied* relative to traditional point-and-click interfaces. Hence, the second aim of this study was to determine whether embodiment had an effect on performance.

A. Executive function

Executive function (EF) is an umbrella term describing a set of cognitive abilities that help manage and monitor thought and behaviour, specifically for novel situations [5]. Research has identified skills integral to EF including planning, cognitive flexibility, self-regulation, and inhibition [6]. EF have a protracted period of development, with noticeable differences witnessed between children as young as five and seven years of age [7]. These were the target age groups for this investigation given that the former represents the first year of formal education in the UK, and that between group performance comparisons would validate the developmental sensitivity. A recent review of EF interventions asserted that efficacy depended on the tasks engagement, progressive difficulty, specificity (i.e. target a single EF), and interestingly, that physical activity had an ameliorative effect on EF [8]. So, here a new computerized EF task was developed to assess a facet of EF; planning.

B. From moving disks to hopping frogs

In developmental psychology the canonical task used to assess cognitive planning is the Towers of Hanoi (TOH)[9], and there have been various iterations (e.g. Tower of London). In the task participants are presented a wooden base with three pegs and three detachable rings that differ in width. To begin, each ring is placed on the left peg, stacked broadest to slimmest in ascending order. The goal is to achieve the same ring configuration on the right hand peg by moving each ring individually, without placing a larger ring on top of a smaller one, and to do so in a single turn after mentally formulating a plan. Success in the TOH requires carefully breaking down the problem into its constituent sub-goals (or *operators*), mentally simulating each operator to update progress, determine whether that operator is optimal, and maintain the task rules in memory [10]. The typical performance metrics of the TOH task include the number of moves made and the time taken to make the first move, and these were adopted for this study. The number of moves gives an indication of planning ability; those who take fewer moves to complete the task demonstrate effective planning skills. Time to first move provides a temporal indication of planning, with previous literature showing that longer planning time often – but not always – equates to better performance [10]. A possible explanation for the development of planning skills is children's learning through interaction with the environment, given that much of the knowledge children garner occurs as a result of play. To test this children played the game using two different interfaces: a keyboard and an electronic floor mat.

Electronic floor mats required players to stand upright and step between nine direction keys in a 3 × 3 grid. Each square on the grid has a pressure sensitive sensor embedded to respond to the user's foot position. Users have the option to return to the central neutral square before moving to the next, or to step from one direction key to another. By comparison, use of the keyboard only required participants to sit down, press the directional keys on the keyboard and attend to the computer monitor. Hence, the floor mat afforded a physically interactive version of the same media, thereby allowing children to embody cognitive elements of the task.

C. Embodied cognition and executive function

Embodied cognition is the theory that our thoughts and subsequent behaviour originate in early sensorimotor interactions with the environment; that the act of thinking involves motor schemata [11]. With regards to EF, a number of studies indicate that physical action has a positive effect on task performance. A recent study investigated effects of gesture on children's set shifting – a facet of EF – while completing the Dimension Card Change Sort task (DCCS) [12]. The authors noted that the most proficient sorters were more inclined to volitionally gesture during their attempts to the sort each card, and also, that those who produced accurate hand gestures while explaining their sorting strategy also tended to score higher. The results indicate that motor action supported children's conceptual understanding of the task.

One possible explanation for these observed effects is that the inclusion of physical action allows the individual to 'offload' cognition [13]. In other words, embodied actions allow children to draw on their experiential knowledge (what they have already learnt through play), and also, to create new associations between motor action and outcomes. Thus, the floor mat provided the opportunity to determine the significance offloading cognition would have on task performance.

So, the primary aim of this study was to establish the developmental sensitivity of the task, with a secondary consideration of embodied effects. The hypothesis were as follows:

1. Children aged seven will out-perform children aged five on the planning task
2. The embodiment of action afforded by the floor mat would improve participants task performance relative to the keyboard

II METHOD

A. Participants

11 children from year one (M = 66.09, SD = 3.12) and 13 from year three (M = 90.50, SD = 2.88) took part in the experiment (age provided in months). Participants were recruited through the schools administration. Once parents gave written consent participants also gave verbal assent before taking part. The study complied with Heriot-Watt University's ethical research policy.

B. Materials

Children played the game on a Dell Precision M4800 laptop. In the keyboard condition children were seated and played the game by pressing the directional keys. The floor mat was a PlayStation ® Dance Dance Revolution mat equipped with eight functioning direction keys (the center square is neutral). The game, Slippy's Adventure, was developed on Adobe Air. For each level participants were presented a plan view of a pond with an array of lily pads. Animations were added for frog jumps, lily pads rotation, lily pad sinking, and a 'thumbs up' from the frog once a level was completed. Each operator lily pads was green, with the exception of the golden target pad.

Slippy's Adventure

The parameters for the Slippy's Adventure were inspired by previous work examining planning in a similar age group. In their version of the TOL task Nitschke et al. children completed 3 and 4 move problems, reporting age related differences [14]. The two task presentations are shown below to show the analogy drawn between the game and the standard tower configuration:

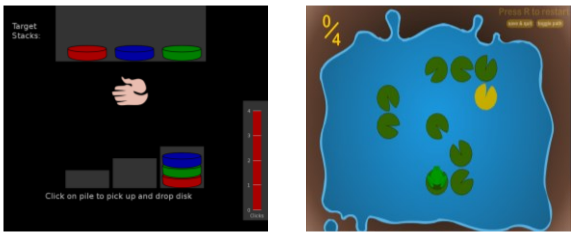

Figure 1: Tower of London (TOH; image courtesy of PEBL [15]) and Slippy's Adventure 4 operator problem.

As their findings noted an effect of age and planning complexity we sought to replicate these findings with a similar age group.

C. Design

All participants played the game using both modalities with presentation counterbalanced. Hence, the study was a 2 × 2 mixed design with a within groups factor of modality (keyboard, floor pad) and a between subjects factor of age (5 years, 7 years). The dependent variables were the mean number of moves made by participants and the time taken to make the first move (TTFM).

D. Procedure

Children took part in the experiment singly, in a dedicated space within their school. To begin the child was introduced to the game and the experimenter carefully explained the rules:

- Slippy cannot jump diagonally
- A lily pad will sink once 'hopped' off
- Slippy's goal is the golden lily pad
- Slippy needs to get there in as few hops possible

Participants completed a block of 10 practice levels before testing. This practice block did not require planning. The trial block included 20 levels. Levels 1-10 could be completed in an optimum of 3 moves. Levels 11-20, could be completed in an optimum of 4 moves. This allowed the investigator to examine the relationship between age and planning depth. Children played the game twice over a week period with the keyboard at one session and the floor mat at another.

III RESULTS

A. Number of moves

To begin, a 2 × 2 mixed ANOVA was conducted to investigate how the between-subjects factor of age (5 years, 7 years) and within-subjects factor of interface (Keyboard, Floor Mat) affected the number of moves participants took to complete the game.

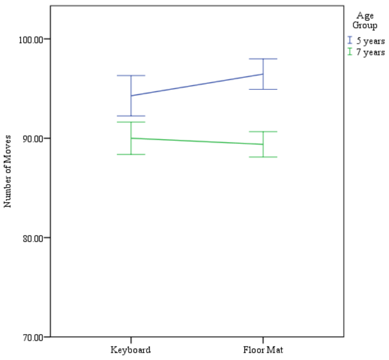

Figure 2: The mean number of moves made by participants for each modality (Note: the y-axis begins at 70, this was the optimum number of moves to complete the game)

A significant effect of age emerged whereby over the course of both testing sessions the older children completed the game in less moves (M = 89.69, SD = 5.18) to the younger group (M = 93.36, SD = 5.93), F (1,23) = 10.75, $p < 0.05$, $n_p^2 = 0.33$. There was no significant effect of modality (p = 0.61), suggesting that children performed equally well using both devices. No modality × age interaction occurred (p = 0.36). The number of moves made by participants in the task was similar for both modalities.

Using the keyboard, the younger children made on average more moves (M = 94.27, SD = 6.74), in comparison to older children (M = 90.00, SD = 5.86), though this difference was not significant (p = 0.61). While using the floor mat 5 year olds again made slightly more moves (M = 96.45, SD = 5.09) relative to children aged 7 (M = 89.38, SD = 4.61) and once again this different was not significant (p = 0.61). Next, the effect of planning depth was investigated. This required equating participants' scores for levels that required both 3 and 4 moves. So, a standardized metric was calculated by dividing the number of moves made by a participant in the first 10 levels by 30 (i.e. dividing by the optimal number of moves) and the second set of levels by 40. The created metric is referred to as Efficiency Score; the more the score deviates from 1 the more a participant deviated from a perfect score.

Examining participants efficiency scores × planning depth revealed that all children performed significantly better on the 4 move levels (M = 1.25, SD = 0.10) compared with the 3 move levels (1.40, SD = 0.14) on the keyboard F (1,22) = 31.56, $p < 0.001$, $n_p^2 = .59$. A similar performance pattern emerged from the floor mat, whereby the 3 move levels caused participants to make significantly more moves (M = 1.38, SD = 0.14), relative to 4 move levels (1.28, SD = 0.07), F (1,22) = 14.36, $p < 0.05$, $n_p^2 = 0.11$.

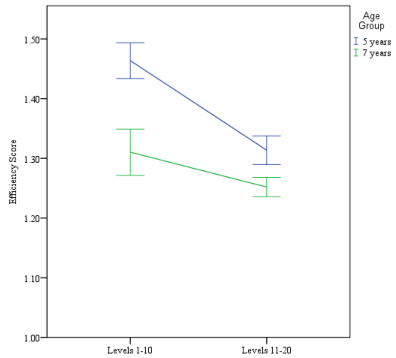

Figure 3: Participants efficiency score for both difficulty levels while using the floor mat

Age differences emerged when children played the game using the floor mat, such that children aged 7s planning score was significantly better, F (1,22) = 12.72, $p < 0.05$, $n_p^2 = 0.37$ indicating that children this age mastered the floor mat to a greater degree.

B. Time to first move (TTFM)

Overall, participants spent longer planning their first move on the keyboard (M = 7.88, SD = 2.55) compared to the floor mat (M = 7.06, SD = 2.09) and this difference was approaching significance (p = 0.058). There was no main effect of age (p = 0.75) and no age × modality interaction (p = 0.76).

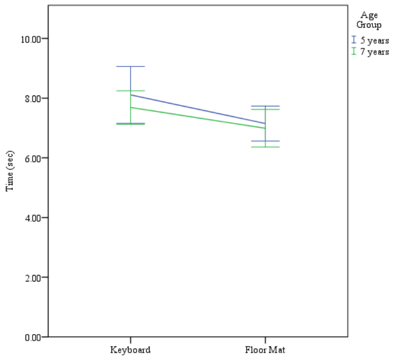

Figure 4: Participants mean TTFM (seconds) with respect to age group and modality

In the next analyses the effect of planning depth (3 move, 4 move) × age (5 years, 7 years) was investigated for each modality independently.

IV DISCUSSION

A. Developmental Sensitivity

The following experiment sought to determine the utility of a new planning task with children aged 5 and 7 years. The primary hypothesis that significant differences would emerged between the two groups on measures of planning was upheld. In that respect, the group differences on the number of moves made in the game demonstrate the tasks sensitivity to age related differences in executive processes. A potential explanation relates the features of effective planning outlined by Anderson [10]. To succeed in the TOH task requires the ability to pick apart the problem into it respective operators, and from there determine the best course of action to take, evaluate each move in turn, and remember the rules. The results here suggest that children aged seven could perform each of these abilities to a greater degree than the younger group on Slippy's Adventure. This result also suggests that the configuration and presentation of the game engages children's executive processes and therefore is an appropriate tool to study childhood cognition. Although this finding is promising in terms of the developmental sensitivity of the game much work is still to be done to determine how executive skills relate to performance. Because no baseline measure of EF was gathered before taking part, it can only be stipulated that the game is a pure test of planning. Hence, future work will add baseline measures of EF suitable for children to determine what facets of EF are engaged during the task.

B. Conceptual mapping

Another possible explanation rests on the functionality and conceptual mapping of the two devices. Using the keyboard allowed children to navigate the frog's direction without an intermediate action, whereas the floor mat at did (i.e. returning to center). This may have interfered with children's representation of the task. It was possible to direct the frog in any possible direction immediately after moving in the keyboard condition. However, the addition of an intermediate 'step back to center' action could have reduced the extent that children embodied the frog's actions whilst using the floor mat. It may well be that for an embodied action to have an effect on performance the action must not only relate to motor schemas, but also occur in a similar action sequence. Certainly, the motor interference effects are widely reported to have a degrading effect on task performance if the movement is congruent or incongruent to expectation. Glenberg and Kashak demonstrated this effect by asking participants to evaluate a sentences plausibility by either pulling or pushing a lever [16]. When the sentence included a word that primed directional expectation (i.e. close the drawer), and the appropriate response was counter-directional (i.e. pulling the lever) participants judgments were poorer. As such, performance differences may not have arisen between the two modalities due to the functionality of the floor mat and the experienced incongruence between stepping back to center without reciprocal action in the game.

A logic step forward therefore may be to compare performance between devices with the same mapping, but differ in the mode of physical interaction. Peripheries such as the Leap Motion controller could be programmed to function along the same lines as the keyboard. As discussed earlier, hand gestures provoke previously learned motor schemas, assisting children's problem solving efforts. Hence, the Leap motion could be the ideal interface which to investigate the role of gesture to children's planning.

C. Interface familiarity

Another feature that may explain performance similarities between the two interfaces is that children are generally more familiar with the functionality of a keyboard. Certainly, the TTFM data indicate that children were more willing to spend extra time planning while pressing the directional keys. So, a future consideration would be to control for children's familiarity with different technologies via a parent-report measure of media use.

CONCLUSION

Here, children took part in a newly created EF task using two user interfaces differing in the level of physical engagement. The findings suggest the task is sensitive to developmental changes in children's EF. The physical interaction afforded by the mat did not ameliorate performance as suggested by the theory of embodied cognition however, this finding calls for a more stringent investigation of body-cognitive processes.

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