**Virtual Reality Based Executive Function Training in Schools:**

**The Impact of Adaptivity on Executive Function and Motivation**

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**Abstract**

Executive function (EF) is a skill that is essential in many aspects of daily functioning and as such is a pertinent target for cognitive training protocols. With current findings about EF training being inconsistent, work is now needed to understand the core components that ensure successful training. A key component that is often cited as essential, but which lacks solid empirical justification is training adaptivity, which is thought to improve participant motivation and support engagement. Therefore, the present study aimed to explore the relationship between adaptivity and motivation, in virtual reality (VR) based EF training with primary school-aged children. Sixty participants were allocated to one of three conditions: VR adaptive training, VR non-adaptive training, and a passive control group. Training in VR conditions consisted of 12 fifteen-minute sessions, delivered over 4 weeks and was delivered using the cognitive training game Koji’s Quest, developed by NeuroReality. All participants completed EF tests at pre- and post- time points. Participants in the VR conditions also completed motivation measures after the training. Results suggest that the adaptive training might influence the switching response over time, but further analyses did not confirm significant differences, possibly due to the small sample size and the high scores variability. Although no differences were observed on the quantitate measures of motivation, qualitative feedback did indicate that perhaps motivation may have been a contributing factor. Results provide initial evidence that short term VR cognitive training may be effective in improving cognitive flexibility in primary aged children, however due to the small sample size and high variability, results are tentative, and further research is necessary. Findings are discussed in terms of the implications for educational application.

Key words: Executive function, adaptivity, virtual reality, cognitive flexibility, motivation

1. **Introduction**

This research aims to consider the impact of adaptivity in the context of executive function (EF) training and asks two questions: how might adaptivity impact EF and how might adaptivity impact motivation. Understanding the associations between adaptivity, EF and motivation is important for two reasons. Firstly, it is only by understanding the relationship between adaptivity and motivation that they can be controlled for in research. This knowledge will therefore speak to accurate and meaningful research design. Secondly, the impact of adaptivity on motivation has implications for participant experience, especially where training is carried out over the longer term. If adaptive training is more motivating, then participants are likely to have a more positive and engaging experience, and this has implications for individuals engaging in EF training.

Including a consideration of motivation resonates with the current research field. More recent analysis of EF training literature has focused on problematic design aspects of this field and specifically the choice of control measures. For example, some research utilises an active control measure, where participants are actively engaged in an alternative task, whereas other research utilises a passive control measure, where participants have no contact with researchers, and continue with their regular activities. There has been some suggestion that the use of a passive control measure may be insufficient as this creates significant differences in motivation between groups of participants (Au et al., 2020). This is an area of debate however, with some researchers suggesting that passive control measures may be as effective as active control measures. There is agreement however, in the need to consider the impact of non-specific effects, including motivation, on EF training more directly (e.g., Masurovsky, 2020).

* 1. **Executive Function**

Research about EF suggests a range of definitions, and this diversity can sometimes serve to obscure, rather than clarify the concept. For example, EF can be considered in terms of problem solving (Zelazo et al., 1997) as a control mechanism, which regulates human cognition (Miyake et al., 2000), or as top-down mental processes (Diamond, 2013). In their systematic review, Baggetta & Alexander, (2016) draw out the commonalities of this complex construct and consider three elements to be especially significant. Firstly, EF guides actions essential to learning and everyday life; that EF contributes to the monitoring and regulation of such tasks; and that EF pertains to cognitive, socioemotional and behaviour domains of activity. This research therefore will adopt the definition: EF is a set of higher order cognitive processes through which learning and everyday goals are realised. They comprise the fundamental building blocks of how we plan, execute, monitor and regulate tasks, and impact our cognitive, socioemotional and behavioural responses.

Whilst there is common agreement that EF is composed of three components: working memory, cognitive flexibility and inhibitory control (Diamond, 2013), disagreement remains as to the relationship between these components. For example, the unity and diversity model posited by Miyake & Friedman, (2012) considers EF in terms of updating, shifting and inhibition.

This triadic and parallel model considers there to be common components, whereby the different components are working together, as well as specific components for updating and shifting. In contrast, the model proposed by Diamond & Ling, (2019) is hierarchical. This model suggests that the two primary components are working memory and inhibitory control, and it is through these, that the third component, cognitive flexibility is made possible. It is through these components that the higher-level skills of reasoning, problem solving, and planning are executed.

These models represent slight differences in the relationship between these components. For example, in the Miyake model, cognitive flexibility (shifting) results from the combination of common EF components, and a shifting specific component. In contrast, the Diamond model suggests that cognitive flexibility draws on working memory and inhibitory control components.

There is broad agreement in the importance of EF to a wide range of outcomes, and researchers agree that where deficits in EF are identified, individuals are at risk in several ways. There is evidence that for adults, EF deficits have been associated with poorer health outcomes (Gray-Burrows et al., 2019) and perceptions of quality of life (Davis et al., 2010). For children, individuals with EF deficits are more likely to experience difficulty with school readiness and academic achievement (Diamond & Ling, 2019) and reading and Maths skills (Strobach & Karbach, 2021, p. 335). There is also evidence suggesting that EF may moderate children’s ability to learn from Maths instruction (Ribner, 2020) and the ability to engage with mindfulness (Butterfield & Roberts, 2022). Effective EF training, therefore, has the capacity to change lives.

EF training has been shown to be successful in a range of areas and for children of different ages. For example, van Bers et al., (2020) examined the effect of cognitive flexibility training with 3-year-old children, finding evidence of near transfer. In their research Prager et al., (2023) found that three brief EF training sessions improved the number skills (but not general mathematics skills) of pre-school children. There is also emerging evidence that EF training can be used to reduce the achievement gap between low and high achieving younger students (Wang et al., 2019). In addition, Johann & Karbach, (2020) compared the effects of game-based training, standard training and a control group, which targeted working memory, inhibition or cognitive flexibility, with children aged 8-11 years. Results indicated that participants allocated to the game-based cognitive flexibility training group, and the game-based inhibition training group made greater improvements in reading, as compared to the control group.

* 1. **Adaptivity**

Adaptivity is a feature of games which involves the adjustment of difficulty in response to the competence of the player and has frequently been employed in research exploring cognitive training. This includes interventions designed to support reading (Karbach et al., 2015) and maths (Vanbecelaere et al., 2021), to support children with additional learning needs (Dunning et al., 2013; Holmes et al., 2009; Söderqvist et al., 2012), with young adults(Vanbecelaere et al., 2021), and with children and adolescents (Plass et al., 2019).

There is ample evidence that adaptivity has a positive impact on training outcomes. For example, Pedullà et al., (2016) compared adaptive and non-adaptive cognitive training with a participants group with multiple sclerosis. They found significant differences in changes to sustained attention and information processing speed for the adaptive training group only. In addition, Karbach et al., (2015) compared adaptive and non-adaptive working memory training with young children. Adaptive training led to larger training gains and transferred to a standardised test for reading. In addition, Vanbecelaere et al (2021) found that children exposed to an adaptive version of a numerical skills training game learned more efficiently. The training impact of adaptivity is clearly evidenced, however, the mechanism by which it is effective is less clear.

Cognitive explanations of adaptivity are most frequently cited within the literature. One possibility is that adaptivity is effective because it is more likely to lead to generalisable learning strategies (Diamond & Ling, 2019). It has been suggested that this is because training which is not adaptive leads to task-specific problem-solving strategies whereas training which is adaptive and constantly changing the parameters of a task does not allow this, which leads to the learning of more generalisable strategies (Johann & Karbach, 2021). Plass et al (2019, p.59) link this to the *Zone of Optimal Engagement*, whereby tasks are always in the right range of difficulty for the individual. The right range of difficulty for any individual is always changing, because they are always learning, and therefore one of the conditions of successful training is create a mismatch between what you need to do, and what you can do (V. E. Johann & Karbach, 2021).

Non-cognitive explanations for adaptivity suggest that it may be effective because it changes the learning experience. For example, training which is adaptive may well create a more rewarding experience and therefore increase the motivation of the individual to succeed. In line with self-determination theory (R. M. Ryan & Deci, 2000), it is arguable that adaptive training may meet the individual’s needs of competence, autonomy, and relatedness more effectively. This in turn may enhance perceptions of well-being and increase resilience and determination for learning. There is some emerging evidence suggesting a relationship between adaptivity and motivation. For example, Koskinen et al., (2023) found evidence that situational interest increased when adaptivity led to decreases in difficulty, but that situational interest decreased when adaptivity led to increases in difficulty. In addition to this, Vanbecelaere et al (2021) hypothesised that adaptivity may impact the confidence of the learner by reducing the failure experienced by the individual. However, when adaptive and non-adaptive group were compared by a measure of Maths anxiety, differences were not significant.

One further consideration is that the impact of adaptivity may be affected by individual differences. For example, Plass et al., (2019) compared adaptive and nonadaptive versions of a digital game designed to train cognitive flexibility with 11–15-year-olds. Although there were no differences overall, there were differences between the age groups, with older participants benefiting more from adaptivity than younger participants. In addition, research demonstrates some evidence for compensation effects, with those individuals with the weakest performance at baseline benefitting the most from adaptive training (Karbach et al., 2015; Titz & Karbach, 2014). Additional research also points to the possibility that individual differences in need for cognition (Jaeggi et al., 2014) and effortful control (Karbach et al., 2015) may also impact the experience of adaptivity.

* 1. **Research questions and hypotheses**

Therefore, although prior evidence sufficiently demonstrates the potential of EF training, and the importance of adaptivity as a core component of EF training, what is missing from the literature is why adaptivity is effective. Prior research points to both cognitive and non-cognitive explanations. The primary aim of this research therefore is to understand the impact of adaptivity on children’s EF and reported motivation: how might adaptivity impact EF and how might adaptivity impact motivation. Specifically, understanding how EF and motivation changes because of adaptive VR training will provide insight into how, and why adaptivity is effective.

Consequently, this study aimed to test the following hypotheses:

*H1*: Participants will show greater EF development after adaptive training, as compared to the passive control and non-adaptive training conditions.

*H2*: Participants will report higher levels of motivation in the adaptive training condition, as compared to the non-adaptive training condition.

1. **Method**
   1. **Participants**

Seventy participants (aged 8-11 years) from UK Primary Schools were recruited with support of the schools to disseminate information about the research. (Inclusion and exclusion criteria are detailed in Supplementary Material, Tables S1). All participants gave informed consent.

Participants were randomly allocated to one of three conditions: VR adaptive training, VR non-adaptive training and passive control. Of those participants allocated to the VR conditions, twenty-four had no previous VR experience, nine had occasional VR experience, and six had regular VR experience.

Six participants withdrew during the study, and a further four were excluded from the analysis due to completing less than fifty percent of the training (Fig. 1). This cutoff was chosen as it was judged to be the minimum time to allow participants to learn how to play the games, and begin to make progress within them, and is comparable to other research in this area (Plass et al., 2019; von Bastian & Eschen, 2016). A final sample of sixty participants was analysed (F = 25; M = 35, *M* = 9 years, six months, *SD* = 8.73) (Table 1).

**Figure 1**

*Participant flow chart*

A diagram of a flowchart

AI-generated content may be incorrect.

*Note*: HMD discomfort – 1 participant withdrew as they found the VR headset uncomfortable to wear; Potential cybersickness – 1 participant withdrew as they experienced mild nausea

**Table 1**

*Table showing biographical data by condition*

|  |  |  |  |
| --- | --- | --- | --- |
|  | Adaptive | Non-adaptive | Control |
| No. | 20 | 19 | 21 |
| Mean age in years | 9 years 7 months | 9 years 4 months | 9 years 10 months |
| Girls /boys | 10 /10 | 8 /11 | 7/14 |
| Special Educational Needs (SEN) | 2 | 3 | 4 |
| VR experience:  Regular/Occasional/Not at all | 4 /6 /10 | 2 /3 /14 | N/a |

* 1. **Materials**
     1. **Virtual Reality Head-Mounted Displays**

Pico Neo 3 Pro were used to deliver the VR experience. This included a head mounted display (HMD) and two handheld controllers which enabled the user to interact and control the experience, and which also provided haptic feedback. The Pico Neo 3 Pro has a refresh rate of 72/90z, and a 98° field of view. Pico Neo has been successfully employed in prior research, including that with children (e.g., (Hindman et al., 2024; Luo et al., 2023).

* + 1. **Executive Function Training**

The research used Koji’s Quest; an EF training game created by Neuroreality. In the game, the player crash lands on a mysterious planet, where they can explore five different worlds, each of which is based on different neuropsychological paradigms, for example, the Wisconsin Card Sorting Test and Go/No Go tasks (Table 2). Prior evidence suggests that Koji’s Quest is effective in training cognitive skills with children in clinical populations (van de Wouw et al., 2024). For all participants the difficulty level started at 500, and difficulty levels varied from 100 to 1000 based on a 3-up 1-down staircase. After two training sessions, participants in the non-adaptive condition only had their difficulty level fixed. This meant that for this condition, the difficulty level did not adapt to performance. For participants in the adaptive condition the difficulty level adapted to performance.

**Table 2**

*Koji’s Quest worlds, and the neuropsychological paradigms upon which they are based.*

|  |  |  |
| --- | --- | --- |
| World |  | Associated neuropsychological paradigms |
| Mystical Lake |  | Wisconsin Card Sorting Test  Set shifting  Go/No-Go tasks |
| Mayan Temple |  | WAIS-IV Block Design task  Mental rotation paradigms |
| Nautilus Underwater Memory |  | Paired Associates test  Corsi Block-tapping task  Spatial span test |
| Galactic Diamond Belt |  | Visual search tasks, such as D2 test |
| Alien Outpost |  | Useful field of view task  Dual task paradigms |

Participants were able to navigate between the different worlds, in the order they preferred. Across the duration of the training, each world would be visited multiple times, allowing participants to improve on speed and accuracy. Overall, participants in the VR adaptive training condition spent 1,798 minutes on training, compared to 1,845 minutes for the VR non-adaptive training condition. (For more detail about time spent on specific games, please see Supplementary Material, figure S1)

* + 1. **Measures of Executive Function**

Participants were tested at pre- and post- time points for EF ability, specifically cognitive flexibility, inhibitory control and working memory.

The Trail Making Test (TMT) was chosen as the test for cognitive flexibility because of its high construct validity (Sánchez-Cubillo et al., 2009), and previous successful use with children (Reitan & Wolfson, 2004). For the TMT, response times were recorded for Trail A and Trail B and the switching time (Trail A-Trail B) was calculated.

The attention network task (ANT) (Fan & Posner, 2004), is widely used as a measure of inhibitory control(Johnson et al., 2008; Rueda et al., 2004). For the ANT, alerting, orienting, and conflict network scores were recorded, as well as the mean response time for correct responses.

Forward (FDS) and backward digit span (BDS) were chosen as the tests for working memory and have been previously used as cognitive measures with children(Rosenthal et al., 2006): Forward 2-error maximal length and backward 2-error maximal length were recorded.

* + 1. **Motivation**

Two measures were chosen to measure participants’ perceptions of motivation. Firstly, the Situational Motivation Scale (SIMS) (Guay et al., 2000) was used. This scale was chosen because of its wide use in educational settings (Stolk et al., 2018), including cognitive training (Kolovelonis & Goudas, 2022), and adaptivity (Koskinen et al., 2023). In this scale, participants are asked about their motivation for doing an activity. Participants are given a series of reasons and mark the extent to which each reason matches why they have been doing the activity. Participants are asked to rate on a 7-point scale from ‘doesn’t match at all’ to ‘matches exactly’. Data provides individual scores for intrinsic motivation, identified regulation, external regulation and amotivation, as well as an overall self-determination score. Sample items are provided in Supplementary Material, Table S2.

Secondly, a brief feedback questionnaire was used. This was administered to participants at the end of the training period. The first item was “have you learnt anything from playing Koji’s Quest?”. For those responding ‘yes’ a second item was given: “what have you learnt from playing Koji’s Quest?” Children were given time to write a response in as much or as little detail as they wanted, or to give responses verbally. Thematic analysis of both children’s responses included phases of analysis: familiarisation, generation, searching, reviewing, defining, as defined by Braun & Clarke (2022). A reflexive thematic analysis (Braun and Clarke, 2006) considered responses at a semantic level, and themes were considered prevalent based on either the number of instances and/or the number of different speakers.

Both quantitative and qualitative measures of motivation were chosen for two reasons. Firstly, given the age of the participants, it was possible that some may find completing a longer questionnaire problematic. Secondly, it was important to give participants the opportunity to voice responses to the training that may have been absent from the Situational Motivation Scale.

* + 1. **Mindset**

To control for potential differences between participants in terms of attitudes and beliefs about learning, the three-item Growth Mindset Scale (GMS) (Dweck, 2021) was used to measure participants beliefs about the nature of intelligence. This scale has been widely used in educational contexts(Yu et al., 2022), and to assess changes after cognitive training(Chen et al., 2022).

* 1. **Procedure**

Participants were allocated to one of three groups: VR adaptive training, VR non-adaptive training, and passive control. Students in the VR conditions were blind as to which group they had been allocated. Participants completed EF tests (TMT, ANT, FDS and BDS) and GMS at pre- and post- time points. Participants also completed the SIMS and a short feedback questionnaire regarding their experience of Koji’s Quest at the end of the training. Training sessions were delivered during the school day, at school, and were delivered by the research team. Participants completed a maximum of 12 fifteen-minute sessions of VR cognitive training using Koji’s Quest over the course of 4 weeks. The study was completed in a six- week period: Pre- testing occurred in the week preceding the training, and post- testing occurred in the week after.

* + 1. **VR Adaptive Training**

The game was set to an adaptive difficulty level, meaning that that the difficulty of the games changed in line with the performance of the participant.

* + 1. **VR Non-Adaptive Training**

Participants accessed the first two sessions of Koji’s Quest at a variable difficulty level, to establish a baseline level appropriate for each individual. For the remaining sessions, the game was set to non-adaptive, meaning that the difficulty of the games did not change in line with the performance of the participant.

* + 1. **Control**

Participants completed EF tests (TMT, ANT, FDS and BDS) and the GMS at pre- and post- time points. Participants otherwise continued with class work as normal.

* 1. **Analysis**

To understand whether the experimental groups were comparable in terms of age, mindset, gender distribution and previous use of VR, a series of One-Way ANOVAs, Chi-Square and Fisher’s exact test were conducted. To understand training effects, firstly a series of 2x3 mixed factorial ANOVA was utilised to examine differences in metrics of executive functioning (task switching, attention and working memory) across groups. A further analysis of post training motivation was undertaken using a combination of t-tests and supplemented with a qualitative analysis of perceptions of learning to provide a holistic understanding of the contribution of adaptivity.

1. **Results**
   1. **Participant Characteristics**

When examining the experimental groups for comparability there were no significant differences observed in terms of mindset scores (*F*(2, 57) = 0.11, *p* = .900.), sex (X2 (2, *N* = 60) = 1.17, *p* = .556) or level of previous VR use (two tailed p = .341). However, there was a statistically significant difference observed in age, *F*(2, 57) = 3.40, *p* = .040, η2 = .11. To examine this further Tukey corrected post hoc tests were conducted demonstrating that the difference was primarily between the non-adaptive group and the control group (*M* difference = -6.89, 95% CI [-13.28, -0.50], *p* = .032.

* 1. **Hypothesis 1: Participants will show greater EF development after adaptive training, as compared to the passive control and non-adaptive training conditions.**

Table 3 shows the mean EF test scores, at pre- and post- time points, for the adaptive, non-adaptive and control groups. *P-*values and effect sizes are given for the pre-post training effect.

* + 1. **Trail making Test**

An analysis of the residuals was performed to check the data met the assumptions for a two-way mixed ANOVA. Inspection of boxplots and standardised residuals indicated there were no significant outliers present in the data (+/- 3 SD). The data were approximately normally distributed as demonstrated by Z-scores within the +/- 1.96 range for both skew and kurtosis and histograms that demonstrated an approximate bell-shaped curve. There was homogeneity of variances (p > .05) as assessed by Levene's test of homogeneity of variances.

There was a significant interaction found between condition and time, (*F*(2, 57) = 3.77, *p* = .029, *ηp2* = .12). Overall, this indicates that the impact of time on switching response is dependent on which condition the participants belong to.

A simple main effects analysis was run to examine the relationship further. The main effect of condition was examined at pre and post time points. No significant main effects of condition were found at pre (*F*(2, 57) = 1.9, *p* = .159) and post (*F*(2, 57) = 0.49, *p* = .617) time points.

Second, the main effect of time was examined for each condition. There was a significant main effect of time for the adaptive condition only (*F*(2, 57) = 6.58, *p* = .019). No significant main effects of time were found for the non-adaptive (*F*(2, 57) = 0.01, *p* = .943) and control (*F*(2, 57) = 1.77, *p* = .198) conditions.

Tukey corrected post hoc tests were used to further examine the main effect of time for the adaptive condition. It was observed that switching time at pre time point did not significantly differ from post time point (37.02, 95% CI [-9.46, 83.51], *p* = .16).

It was found that the impact of time was dependent on condition. Simple main effects analysis demonstrated that pre and post time points were significantly different from one another in the adaptive condition only, however, follow up tests failed to confirm a significant difference in switching time.

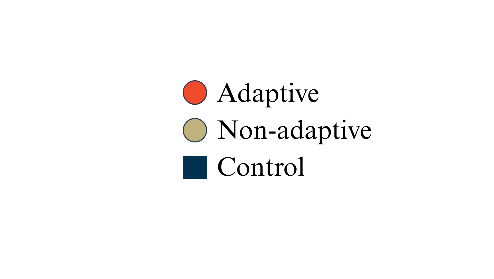
**Table 3**

*Table showing mean EF test scores, P-values and effect sizes*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | |  |  |  | Adaptive training | | |  | Non-adaptive training | | |  | Control | | |  | Pre-post training effect | |
|  | |  |  |  | Pre- | Post- | Diff. |  | Pre- | Post- | Diff. |  | Pre- | Post- | Diff. |  | *p* | *ηp2* |
| TMT switching (s) | | | *M* |  | 86.71 | 49.68 | 37.03 |  | 62.74 | 63.88 | -1.14 |  | 48.12 | 68.47 | -20.35 |  | .029 | .12 |
| *SD* |  | 76.22 | 52.57 | 23.65 |  | 50.19 | 70.61 | -20.42 |  | 61.83 | 65.36 | -3.53 |  |
|  |  |  |  |  | | | | | | | | | | | | | | |
| ANT  Alerting | | | *M* |  | 63.35 | 55.78 | 7.57 |  | 39.82 | 37.16 | 2.66 |  | 45.57 | 64.86 | -19.29 |  | .642 | .02 |
| *SD* |  | 57.85 | 13.25 | 44.60 |  | 18.18 | 21.04 | -2.86 |  | 11.46 | 11.07 | 0.39 |  |
| ANT  Orienting | | | *M* |  | 54.23 | 30.38 | 23.85 |  | 30.92 | 11.05 | 19.87 |  | 38.71 | 54.09 | -15.38 |  | .356 | .04 |
| *SD* |  | 53.77 | 36.26 | 17.51 |  | 107.21 | 74.00 | 33.21 |  | 40.70 | 54.09 | -13.39 |  |
| ANT  Conflict | | | *M* |  | 140.13 | 60.43 | 79.70 |  | 84.32 | 60.13 | 24.19 |  | 115.00 | 70.10 | 44.90 |  | .372 | .04 |
| *SD* |  | 146.59 | 33.55 | 113.04 |  | 106.14 | 83.11 | 23.03 |  | 60.63 | 47.53 | 13.10 |  |
| ANT Mean response time (ms) | | | *M* |  | 748.88 | 727.29 | 21.59 |  | 739.43 | 714.67 | 24.76 |  | 709.49 | 665.10 | 44.39 |  | .684 | .01 |
| *SD* |  | 100.76 | 90.65 | 10.11 |  | 145.86 | 113.76 | 32.10 |  | 94.26 | 95.87 | -1.61 |  |
|  |  |  |  |  | | | | | | | | | | | | | | |
| FDS | | | *M* |  | 5.50 | 5.30 | -0.20 |  | 5.05 | 5.37 | 0.32 |  | 5.05 | 5.38 | 0.33 |  | .122 | .07 |
| *SD* |  | 0.89 | 1.08 | -0.19 |  | 1.08 | 1.07 | 0.01 |  | 0.81 | 0.74 | 0.07 |  |
| BDS | | | *M* |  | 3.70 | 3.75 | 0.05 |  | 3.68 | 3.63 | -0.05 |  | 4.00 | 3.91 | -0.09 |  | .924 | .01 |
| *SD* |  | 0.92 | 1.21 | -0.29 |  | 0.67 | 1.46 | -0.79 |  | 0.95 | 1.04 | -0.09 |  |
| *Note:* TMT – Trail Making Test; ANT – Attention Network Task; FDS – Forward digit span; BDS – Backward digit span | | | | | | | | | | | | | | | | | | |

**Figure 2**

*Graph showing switching time (s) for pre and post time points, by condition.*

A diagram of a graph

Description automatically generated with medium confidence

* + 1. **Attention Network Task**

No significant differences were found for the ANT in terms of mean response time (*F*(2, 57) = 0.39, *p* = 0.684), alerting (*F*(2, 55) = 0.45, *p* = 0.642), orienting (*F*(2, 57) = 1.05, *p* = 0.356), or conflict (*F*(2, 57) = 1.01, *p* = 0.372) subscales.

* + 1. **Digit Span**

No significant differences were found for the forward digit span (*F*(2, 57) = 2.19, *p* = 0.122) or backward digit span (*F*(2, 57) = 0.08, *p* = 0.924).

**Summary**

Results suggest that the adaptive training might influence the switching response over time, however, further analyses did not confirm significant differences, possibly due to the small sample size and the high scores variability.

* 1. **Hypothesis 2: Participants will report higher levels of motivation in the adaptive version of Koji’s Quest, as compared to the non-adaptive version.**
     1. **Situational Motivation Scale**

The Levene test found that the assumption of homogeneity of variance was met for self-determination and the associated subscales. The assumption of normality was met for self-determination, intrinsic motivation and identified regulation as indicated by a series of Shapiro-Wilk tests (*p* > .13) therefore student *t*-tests were carried out. Although the Shapiro-Wilk tests for external regulation and amotivation showed that the assumption of normality had not been met (*p* < .05), analysis of skew and kurtosis z-scores indicated no significant variations from normal distribution, and therefore a series of *t*-tests were applied.

No significant differences in motivation between the adaptive and non-adaptive groups were found. Table 4 shows the mean scores for self-determination and the motivation subscales, for the adaptive and non-adaptive groups.

**Table 4**

*Table showing mean, standard deviation and t-test p-levels for motivation scores, by condition*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Adaptive | | Non-adaptive | | *p-*value |
| *M* | *SD* | *M* | *SD* |
| Intrinsic motivation | 20.10 | 4.01 | 21.32 | 3.96 | .347 |
| Identified regulation | 17.75 | 2.90 | 17.84 | 4.96 | .944 |
| External regulation | 8.95 | 4.56 | 8.58 | 4.77 | .805 |
| Amotivation | 9.60 | 3.65 | 10.58 | 5.55 | .517 |
| Self determination | 29.80 | 14.40 | 30.74 | 23.19 | .880 |

* + 1. **Feedback Questionnaire**

To understand the subjective experience of the training and how this differed between the training groups a feedback questionnaire was provided. Thirty-five responses were collected; sixteen were collected from the adaptive (A) and nineteen from the non-adaptive condition (NA). In response to the initial question, ‘have you learnt anything from playing Koji’s Quest?’, fifteen participants from the adaptive condition, and sixteen participants from the non-adaptive condition responded ‘yes’. Percentages for questionnaire completion, and yes/no responses are illustrated in Figure 3.

**Figure 3**

*Bar chart showing the frequency of participants in each condition responding to feedback questionnaire*

Participants answering ‘yes’ were provided with a follow-up question: ‘what have you learnt from playing Koji’s Quest?’. Thematic analysis of participants’ responses was completed. This included phases of analysis: familiarisation, generation, searching, reviewing, defining, as defined by Braun & Clarke (2022). A reflexive thematic analysis (Braun and Clarke, 2006) considered responses at a semantic level, and themes were considered prevalent based on either the number of instances and/or the number of different speakers. Fifty-seven separate responses were identified, and the following themes were developed: *learning about technology*, *learning about cognition* and *learning about me*. *Learning about technology* included the ways in which participants had learnt about VR, or specific games played in VR. *Learning about cognition* included the ways in which participants had learnt about their own cognition, for example, memory or attention. *Learning about me* included the ways in which participants had learned about their affective responses, including resilience, mindset and self-regulation. The themes developed reflect differences in the generalization of participants perceptions of the learning experience. *Learning about Technology* was concerned with the specific technology (VR) or game (Koji’s Quest) and described experiences and skills which were only useful within the specific experience. *Learning about cognition* was concerned with more generalized skills that could be utilised outside of the experience. *Learning about me* was concerned with a generalized impact of the experience and outcomes that were not directly delivered. The three themes demonstrate a progressive increase in generalization, agency and self-awareness. Illustrative responses for each theme are shown in Figure 4 and the proportion of responses allocated to each theme is shown in Figure 5.

**Figure 4**

*Illustrative responses for each of the developed themes*

*A diagram of a technology

Description automatically generated with medium confidence*

**Figure 5**

*Proportion of each of the developed themes*

**Learning about Technology**

Eighteen responses pertaining to *learning about technology* were collected. This included five (27.8%) from the adaptive condition (A) and thirteen (72.2%) from the non-adaptive (NA) condition. Participants from both VR conditions commented on how they had learnt skills which were specific to the VR experience. This included both specific examples: ‘how to play VR’ (NA), and more general: ‘you can learn by using technology’(A). Some students remarked on being able to master a specific game: ‘I learnt feeding the fish’ (A) or on the novelty of this experience: ‘New stuff and games’ (NA).

**Learning about Cognition**

Twenty-six responses pertaining to *learning about cognition* were collected. This included fourteen (53.8%) from the adaptive (A) condition and twelve (46.2%) from the non-adaptive (NA) condition. Participants from both VR conditions commented on the impact they perceived the training had on their cognition. This included more general comments on the overall impact of the training: ‘It can help you learn better’ (A) and ‘it is a game, and it is learning too at the same time’ (NA). There were also more specific responses, such as ‘It has improved my memory’ (A) and ‘I learnt more concentrating’ (NA).

**Learning about Me**

Thirteen responses pertaining to *learning about me* were collected. This included nine (69.2%) from the adaptive condition and four (30.8%) from the non-adaptive condition. For participants from the non-adaptive group these were about their enjoyment of the experience: ‘it makes you happy’ and ‘I find it very fun’. However, participants in the adaptive group also provided some more nuanced responses. These comments were associated with resilience: ‘to never give up and always give something another go’; mindset: ‘I have learnt that you might be able to change your intelligence’ and self-regulation: ‘it helps me calm down’. This suggests that although both groups benefited from their enjoyment of the training, participants in the VR adaptive training group benefited in more specific ways, such as finding more resilience, improving a growth mindset, or finding new strategies for self-regulation. Percentage differences in the feedback response themes are illustrated in Figure 6.

Further observations were made for this theme, pertaining to age. Participants in Year 6 (in both adaptive and non-adaptive training conditions) gave no responses pertaining to this theme, whereas younger participants (Year 4) were responsible for 100% of the comments associated with resilience, mindset and self-regulation.

**Figure 6**

*Graphs showing A) the frequency of feedback responses, by theme and condition, and B) the percentage of responses in each theme, by condition*

A

B

**Summary**

The conclusions drawn for this hypothesis are less clear. In the SIMS, participants did not report higher levels of motivation after adaptive training, as compared to non-adaptive training. No significant differences were found either for self-determination, or for any of the sub-scales. However, the qualitative analysis of feedback responses indicates that participants in the VR adaptive training condition more frequently perceived the benefits of EF training to be linked to an affective response. The youngest participants in the VR adaptive training associated the training with benefits to resilience, mindset and self-regulation.

1. **Discussion**

The first finding that VR adaptive training leads to greater improvement in cognitive flexibility compared to VR non-adaptive training and control participants resonates with the prior literature. The fact that the VR adaptive training outperformed the control condition provides additional evidence for the efficacy of EF training, and supports the findings of, for example, Johann & Karbach, (2020).This suggests the possibility that VR EF training may be efficacious within an educational setting. The fact that the VR adaptive training also outperformed the non-adaptive condition again resonates with prior literature (Dunning et al., 2013; Holmes et al., 2009; Karbach et al., 2015; Vanbecelaere et al., 2021) and provides some insight into the mechanisms through which EF is strengthened. This research aligns with the views of Diamond & Ling, (2019) who have suggested that effective EF training needs to constantly change the parameters of the task. It is arguable that the constant ‘push’ the participants in the VR adaptive training group experienced, was responsible for the greater improvement in cognitive flexibility, which suggests that a cognitive explanation for adaptivity may be fitting.

Our findings failed to show significant changes in either working memory or inhibition. The first potential reason for this is that the sample size and variability was insufficient to demonstrate differences. However, there is another possibility that warrants consideration, the training itself. Although there were separate games within Koji’s Quest, and they trained different skills, the experience of navigating between the games would have taxed cognitive flexibility. In effect, although the games themselves were providing training for working memory, inhibitory control and cognitive flexibility, the experience may have been more weighted to cognitive flexibility training. This idea is supported by the work of Lee et al., 2024). They point to a link between the development of cognitive flexibility and learning under uncertainty. It may be that the experience of encountering and exploring the virtual world compelled individuals to switch between different problem-solving strategies. In fact, they cite variability in training protocol and switching across tasks as conditions that may well facilitate improvement in cognitive flexibility.

The second finding that VR adaptive training does not lead to higher SIMS scores compared to VR non-adaptive training, stands in contrast to motivational theory which suggests that aligning task difficulty with the skills of the individual should enhance motivation (R. Ryan & Deci, 2000). In this sample at least, there were no significant differences between the VR adaptive and VR non-adaptive training conditions: whether the training adapted to the individual did not appear to be a factor in their overall perceptions of motivation.

One explanation for this is that individual differences may impact the extent to which adaptivity is integral to the experience. For example, in their work, Plass et al., (2019) found differences for adaptivity in an older age group only. One conclusion they provide is that younger users required less adaptivity to keep them challenged. For this sample, it is arguable therefore that even within a relatively narrow age bracket, participants progressed at different paces. For those progressing at a faster pace, the impact of adaptivity could arguably be greater, whereas for those progressing at a slower pace the impact of adaptivity could arguably be much less. The work of Koskinen et al (2023) points to the idea that situational motivation may be affected differently by increases or decreases in difficulty. For those in the adaptive group, both increases and decreases in difficulty were possible, whereas for those in the non-adaptive group, neither were possible. Again, this may mean that there were differences within the conditions that this study has been unable to sufficiently measure. Due to the measures chosen, one of the things that this study was unable to measure was changes in motivation throughout the training period. For example, if the findings of Koskinen et al (2023) are accurate, individuals may experience ebbs and flows of motivation as they encounter difficulty, and then consequently master that difficulty.

The final finding that there are qualitative differences in feedback responses between VR adaptive training and VR non-adaptive training provides potential support for the above argument. Differences in the qualitative responses appear to show a trend: participants in the VR adaptive training group more frequently perceived the benefits of EF training to be linked to an affective response. This aligns with motivational theory(R. Ryan & Deci, 2000), as those participants whose training changed according to their needs more frequently gave responses indicating higher levels of intrinsic motivation. In addition to this, the youngest participants in the VR adaptive training were the ones who associated the training with benefits to resilience, mindset and self-regulation. This points perhaps to a more complex relationship between adaptivity and motivation, as suggested by Koskinen et al., (2023). It is plausible that the higher frequency of responses pertaining to an affective response by younger participants is indicative of a lesser impact of adaptivity for these children. In contrast, the lower frequency of responses pertaining to an affective response by older participants may be indicative of the increased impact of adaptivity.

In terms of other individual differences, it is also possible that adaptivity and therefore motivation was impacted by the differing executive function ability of this sample of children. This sample was designed to be broad and inclusive, and included children with additional learning needs. Research by both Karbach et al., (2015) and Titz & Karbach, (2014) has found in favour of compensation effects, and therefore differences in outcomes could be attributed to this. In addition, although the conditions were assessed for comparability in terms of growth mindset, additional differences such as need for cognition were not assessed and therefore could have been significant.

1. **Implications and Applications**
   1. **Implications**

These findings contribute to our understanding of EF and the mechanisms through which it can be developed. Our finding that EF was improved in the VR adaptive training condition only lends support to research such as Diamond & Ling,( 2019) in their suggestion that adaptivity is a critical ingredient of EF development. Indeed, in this sample, training without adaptivity showed no evidence of EF change.

These findings also contribute to the ongoing discussion regarding the use of suitable control measures in EF research. Our findings that participants experienced no significant differences in terms of situational motivation between the VR adaptive training and the VR non-adaptive training could begin to suggest that non-adaptive training may well be a suitable choice for a control measure. No contact controls are often criticised for creating significant differences in motivation between conditions(Au et al., 2020). These findings suggest that the use of non-adaptivity could be used to deliver training which does not have an impact on EF, but which has the same impact on motivation. However, the findings from the qualitative data suggest caution in reaching this conclusion. Subtle differences between the experience of adaptive and non-adaptive training may well be magnified over longer periods of time. It is possible that the small differences observed after just a four-week training period may be much larger with more sustained training protocols.

* 1. **Applications**

These findings are highly relevant to an educational context. Our findings show that VR adaptive training can be effective in improving cognitive flexibility with short intervention sessions and within a relatively short time frame. This is significant because it shows the feasibility of incorporating this training within schools. Training which takes a longer time may be less likely to be adopted as it will pose a greater disruption to children’s already busy timetables. Training which requires a longer-term commitment may be more likely to be abandoned before completion, if results are not seen for some time. Our research, which deliberately implemented a training protocol which was non-intensive and relatively short term, avoids both pitfalls.

The finding that there were potential qualitative differences between the training conditions also has implications for an educational context. This suggests that the benefits of EF training may be quite diverse, and that children may demonstrate changes in several different areas. Whether or not individuals make demonstrable EF gains in response to training, gains in other areas, for example, in terms of how they understand their own resilience, may well make a difference to their lives. It is important to recognise and acknowledge these changes.

1. **Limitations and Future Directions**

Results suggest that the adaptive training might influence the switching response over time, but further analyses did not confirm significant differences, possibly due to the small sample size and the high scores variability. Therefore, the next step would be to increase the sample size. A larger sample size would arguably be better able to identify small differences between VR conditions and control and useful in ascertaining the impact of VR adaptive training on inhibitory control and working memory. In addition, this short-term study was not able to capture either far transfer effects or any potential long-term impacts.

Future research should also consider the impact of adaptivity over time. This should include not only a consideration of whether the EF effects persist over time, but also the motivational impacts of longer-term training. In addition, it is, of course, essential to consider far transfer. Our tentative finding that VR adaptive training may lead to gains in cognitive flexibility is a first step. The next would be to consider whether those changes can be transferred to other areas, for example, Maths.

1. **Conclusion**

Our findings together suggest that VR adaptive training may be effective in improving cognitive flexibility with short intervention sessions and within a relatively short time frame. They provide initial evidence for the feasibility of VR EF training with primary school-aged children and begin to examine the relationship between adaptivity and motivation.

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