Cognitive-motor interaction during virtual reality trail making

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Abstract—**There is great interest in ecological virtual reality (VR-) based adaptations of traditional pen-and-paper neuropsychological tests. Such adaptations are designed to measure the same cognitive construct(s) as the original test but may also evaluate interactions between such constructs and other functions (e.g., motor), as occurs in daily life. Here we report on translation of the pen-and-paper Color Trails Test (CTT) to a VR-based head-mount device (HMD) implementation. Trails A is a measure of sustained attention, while Trails B measures divided attention. Participants were twenty-seven young (28.02±3.98 years) and twenty-nine middle-aged (55.41±6.60 years) healthy individuals. For young and middle-aged participants, respectively, mean VR-CTT Trails A completion times were 61.77 and 86.70 sec. Mean VR-CTT Trails B completion times were 113.25 and 154.00 sec, respectively. These completion times were significantly longer than those obtained for the pen-and-paper version (*p*<.001). The middle-aged group had longer completion times than young adults for both test formats (*p*<.001), with VR-CTT Trails B separating among the groups better than the corresponding pen-and-paper measure (*p*<.05). Supporting construct validity, completion times were correlated between pen-and-paper and VR-based versions (Trails A: *r*=.63; Trails B: *r*=.60, *p*'s<.001). VR-CTT motor performance was evaluated by quantifying the deviation of the actual reaching trajectories from the hand trajectories predicted by the minimal jerk model. For both age groups, deviations were greater for Trails B relative to Trails A (*p*<.001), consistent with a potential effect of divided attention on motor planning and execution. In sum, our VR-based HMD implementation of the CTT assesses similar cognitive constructs to the original pen-and-paper test (construct validity). Further, as suggested by longer**

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completion times and substantial impact of cognitive demands upon motor performance, this VR-CTT affords enhanced ecological validity and added value by capturing cognitive-motor interactions associated with planning and execution of voluntary reaching movements during the task. We believe that such VR-based adaptations lie at the frontier of neuropsychological testing and will ultimately offer novel insights into our understanding of multimodal human function in the real world.

Keywords—Color Trails Test; executive function; attention; processing speed; neuropsychological testing; virtual reality; cognitive-motor interaction.

I. INTRODUCTION

Virtual reality (VR) technologies have advanced extremely rapidly in recent years. In addition to new technical features for precise stimulus delivery and response measurement, as well as enhanced usability, low-cost VR is now widely accessible. The most accessible VR system is the head-mount device (e.g., HTC Vive, Oculus Rift), which is designed for personal operation. In addition to its continued popularity for entertainment, VR is now being applied in a variety of 'serious' contexts, ranging from surgical simulation to the study of human performance and psychological function [1, 2].

Recently, we and others have proposed that VR-based adaptations of traditional neuropsychological assessments may allow measurement of cognitive function in a manner more relevant to performance of daily life activities, including the interaction among multiple functions (e.g., sensory, cognitive, motor) [2-7]. Practically, this approach involves adapting traditional (generally pen-and-paper) neuropsychological tests to VR-based format. VR-based tests have superior ecological validity in that test performance better captures and more closely resembles real-world functioning [2, 6-11]. Neuropsychological tests measure a variety of cognitive domains, including memory, executive function, attention, and processing speed. Each test involves processes related to these cognitive domains, such as sustained attention, planning, and verbal reasoning, resistance to interference, cognitive flexibility, novelty detection, multitasking, problem solving and sequencing [12].

Among the most popular pen-and-paper tests of executive function, attention and processing speed in research and clinical neuropsychological assessment is the Trail Making Test (TMT) [13, 14]. The TMT consists of two parts: (1) *Trails A*: participant draws lines to sequentially connect circles numbered 1 to 25 on a standard sheet of paper. (2) *Trails B*: participant draws lines to sequentially connect circles but must now alternate between circles containing numbers and letters (i.e., 1, A, 2, B, 3, C, etc.) [15]. The Color Trails Test (CTT) is a culture-fair variant of the TMT in which the participant alternates between circles of two different colors in Trails B (i.e. 1-pink, 2-yellow, 3-pink, 4-yellow, etc.) [16].

We previously reported on a pilot study in which the pen-and-paper CTT was translated from 2D to a 3D VR-based test. In this pilot, CTT was implemented with a large-scale VR system requiring the participant to stand in the middle of a visual scene projected on a 360° dome-shaped screen [17]. Results of the pilot revealed similar patterns of performance on the VR-based and gold standard pen-and-paper versions of the CTT (e.g., longer completion time for B vs. A). Coupled with substantial correlations between corresponding parts, this suggests that the two tests indeed measure common cognitive constructs. Notably, completion times for Trails A and B were longer for the VR version, consistent with greater task difficulty [18] and suggesting the involvement of other functions not measured by the pen-and-paper version [17]. The biggest limitations of large-scale VR systems are high cost and space commitment, making them impractical for widespread use. Thus the **first goal** of the current work is to create a low-cost VR-based CTT adaptation implemented with VR goggles (i.e., head-mount device; HMD).

The **second goal** is to evaluate the construct validity of the HMD VR-based CTT by computing the correlation between corresponding scores on the pen-and-paper and VR-based test. Our **third goal** is to confirm the presence of the expected age effect on our new test by comparing performance of young and middle-aged participants for the VR-based test.

Finally, as the VR-based adaptation involves complex 3D reaching movements rather than 2D line drawing, the **fourth goal** is to explore the relationship between cognitive measures and novel VR-CTT motor measures, demonstrating added ecological value and providing insight on human cognitive-motor interactions in voluntary reaching.

II. METHODS

A. Participants

Participants were twenty-seven young (age: 28.02±3.98 years; education: 16.70±1.85 years; 15 female) and twenty-nine middle-aged (age: 55.41±6.60 years; education: 15.76±2.46 years; 24 female) healthy individuals. Exclusion criteria were motor, balance, psychiatric or cognitive conditions that may interfere with understanding the instructions or completing the required tasks. The protocol was approved by the Sheba Medical Center institutional review board (IRB), and all participants signed informed consent prior to entering the study.

B. Apparatus

For this study, we used a fully immersive VR system (HTC; New Taipei City, Taiwan) including a headset with

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~100° field of view (FOV) angle in the horizontal plan and ~110° FOV angle in the vertical plan. Also included were a controller for user interaction with the virtual environment and two 'lighthouse' motion trackers for synchronizing between actual controller position and corresponding position in the virtual environment.

C. The Virtual Reality Color Trails Test (VR-CTT)

Details regarding translation and adaptation of the CTT from traditional pen-and-paper to VR-based format were previously described for a large-scale VR system [17]. Here we adopt a similar approach but for a VR headset system. Briefly, we used the popular Unity3D VR game engine [19] to develop a virtual environment for the VR-CTT.

In the virtual environment, the two-dimensional (2D) page is replaced by three-dimensional (3D) VR space, effectively adding the dimension of depth to the position of the targets and to the hand trajectory generated by the participant as s/he connects them. Fig. 1 illustrates how the 2D format of the original CTT was translated to the 3D VR-CTT format (Trails A).

The testing procedure was also adapted for the new format. The original pen-and-paper CTT comprises four consecutively administered test levels: (1) Trails A practice; (2) Trails A; (3) Trails B practice; (4) Trails B [16]. Though writing with a pen on paper is highly familiar, manipulation of the VR controller to move an avataric marker within the virtual environment is a relatively unfamiliar skill for most participants. Thus in the first VR-CTT test level, participants practice guided movement of an avataric marker within the virtual space to correctly touch the numbered ball targets. During this level, participants are introduced to the positive feedback received when touching a correct ball (i.e, brief enlargement of the ball) and the negative feedback upon touching an incorrect ball (i.e., brief buzzing sound). Then Trails A practice (two levels), Trails A, Trails B practice (two levels) and Trails B are administered. Notably, Trails A and Trails B is each preceded by two different practice levels. In the first practice level, all balls appear near the center of the visual field, and in the second practice level, the balls are positioned throughout the visual field, approximating the spatial distribution of the balls in the actual testing levels. Throughout the VR-CTT, movement of the avataric marker (a distinct red ball) is accompanied by a gradually fading virtual trail (akin to skywriting) corresponding to the pen lines left on the paper when the circles are connected in the traditional test. CTT and VR-CTT were administered in counterbalanced order across participants.

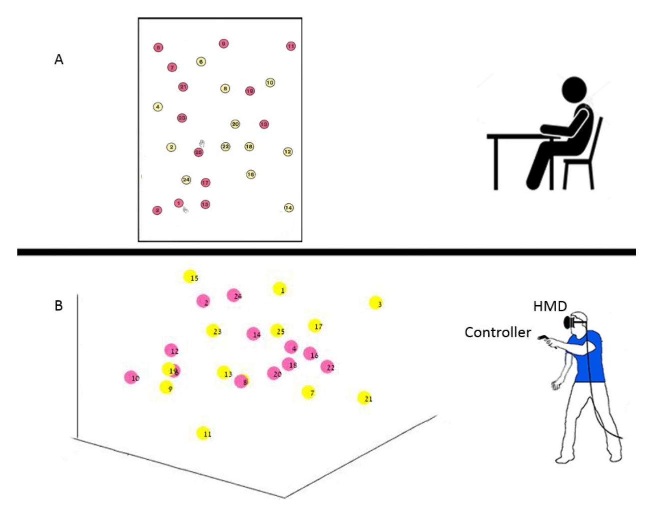

Fig. 1. Translation of CTT to VR format. A) In the traditional 2D CTT, the participant is seated at a desk and uses a pen to sequentially connect numbered circles distributed on a sheet of paper. B) In the 3D VR-CTT, the participant completes the task while standing wearing a VR headset and uses a VR controller to move an avataric marker to sequentially connect numbered balls distributed throughout the virtual space visible in the headset. (Trails A shown.)

D. Quantification of motor performance

Spatial coordinates of the controller position (corresponding to the virtual avataric marker) were recorded throughout the VR-CTT. Custom software written in MATLAB (Mathworks, Inc.) used this data to extract and analyze the 25 target-to-target reaching movements during Trails A and Trails B, respectively.

To investigate whether motor control during Trails B differs from Trails A, we compared actual hand trajectory during reaching movements to an idealized trajectory predicted by the minimal-jerk model of Flash et al. [20]. This mathematical model predicts the hand velocity profile between two points on a plane. The predicted profile is characterized by a bell-shaped curve. As the model was designed to address planer arm movements, and as there is no similar model to account for hand movement in 3D space, we analyzed target-to-target paths that connect targets located roughly on a plane perpendicular to the coronal plane (see Fig. 2a). Fourteen such target-to-target paths were analyzed from Trails A and twelve from Trails B.

The velocity profiles for these trajectories were compared to the profiles predicted by the model, and the difference was quantified as percent deviation (%D). For further details, see Fig. 2b-d.

E. Outcome measures and statistical analysis

For the pen-and-paper CTT and the VR-CTT, completion times for Trails A and B were recorded (t_a, t_b, respectively). $\%D_a$ and $\%D_b$ were calculated for VR-CTT Trails A and B, respectively. For t_a and t_b, construct validity was assessed by correlating t_a and t_b from the VR-CTT with the corresponding scores from the gold standard CTT (Pearson coefficient). Analysis of variance (ANOVA) was used to assess effects of Group (young, middle age; between subjects factor) and Format (pen-and-paper CTT, VR-CTT; within-subjects factor). Cohen's *d* was computed as a measure of effect size. For D%, young and middle-aged groups were compared by between groups *t*-test; %Da and %Db were compared by paired *t*-test. $p<.05$ was considered statistically significant. To verify suitability of parametric statistics, Shapiro-Wilk normality tests were run for each

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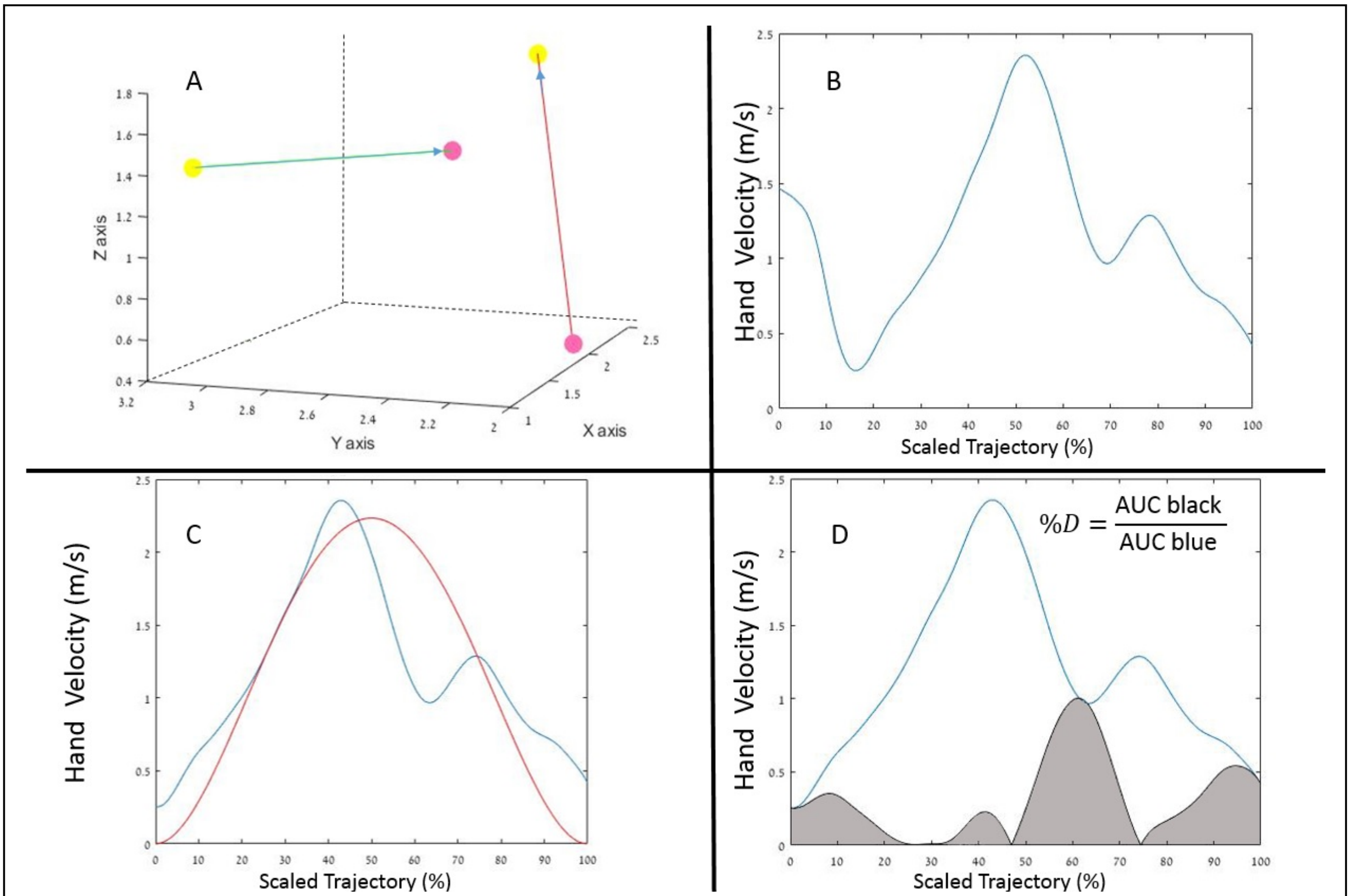

Fig. 2. Quantification of motor performance in the VR-CTT. A) Fourteen target-to target paths were selected from Trails A and twelve were selected from Trails B. Panel A illustrates that the selected paths (exemplified by the green path) were located on planes parallel to the XY plane, and thus the Z coordinates remain relatively unchanged along the entire path; other (unselected) paths (represented by the red path) did not have these geometric characteristics. B) Based on time series position data from the controller, the velocity profile of the trajectory can be computed (in this example, moving from target ball 19 to target ball 20 in Trails A as performed by one young healthy adult). Total movement time was scaled from 0 to 100% to give a scaled trajectory. It can be appreciated that movement toward a target does not stop immediately upon reaching/touching the target, as reflected by the initial positive velocity value and the ensuing decrease in velocity value until it reaches close to zero value. We considered this time point the initial point of the next movement and thus the (initial) portion of the velocity profile until this point was excluded from analysis. C) The actual truncated velocity profile for the trajectory shown in B (blue trace) and the idealized velocity profile predicted by the minimal jerk model (red trace), which takes the shape of a smooth bell-shaped curve. This idealized profile is scaled so that area under the red curve is equal to area under the blue curve; thus mean velocity is set to be equivalent between the two curves and only the shape of the profiles differs. D) The absolute difference between the red and blue curves in C is plotted (black trace), and the area under the curve (AUC) (gray area) is divided by the AUC of the idealized minimal jerk profile (blue trace, cf. panel C), allowing quantification of the deviation from the theoretical model, %D. The smaller the value of %D, the more the movement conforms to the theoretical model. For each participant, fourteen %D values (for the selected target-to-target paths; see A) were averaged for Trails A to give $\%D_a$, and twelve %D values were averaged for Trails B to give $\%D_b$.

outcome variable per group. Of the twelve normality tests, only two indicated non-normal distributions (CTT [pen-and-paper] Trails A Completion Time in the middle-aged group, Shapiro-Wilk statistic=.877, p=.003; CTT [pen-and-paper] Trails B Completion Time in the young group, Shapiro-Wilk statistic=.779, p<.001).

III. RESULTS

A. Performance on the VR-CTT: group differences

Fig. 3 shows Trails A and B completion times (t_a, t_b) for young and middle-aged participants on paper-and-pencil and VR test formats. Statistical analysis revealed large (d>1.0) effects of Group (t_a: $F_{1,54} = 19.95$, $p<.001$; t_b: $F_{1,54} = 26.16$, $p<.001$; longer completion time for middle-aged) and Format (t_a: $F_{1,54} = 243.97$, $p<.001$; t_b: $F_{1,54} = 228.31$, $p<.001$; longer completion time for VR-CTT). The Group x Format interaction reached significance for Trails B (t_b: $F_{1,54} = 4.05$, p=.049) but not for Trails A (t_a: $F_{1,54} = 3.26$, p=.077). We note that the pen-and-paper scores were consistent with the norms for the respective age groups [16, 21, 22].

B. Construct validity

Fig. 4 shows the relationship between performance on the VR-CTT and the gold standard pen-and-paper CTT for all participants. Correlations were in the .6 range, reflecting good construct validity. Correlations for the young group only were: t_a: r=.33, p=.088; t_b: r= .63, p<.001. Correlations for the middle-aged group only were: t_a: r=.56, p=.002; t_b: r=.37, p=.046.

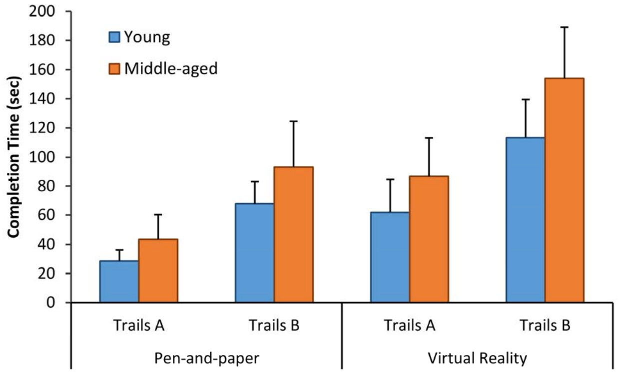

Fig. 3. Trails A (t_a) and Trails B (t_b) completion times (mean+SD) for young (n=27) and middle-aged (n=29) groups on gold standard pen-and-paper CTT (left) and VR-CTT (right). Completion times were longer for middle-aged vs. young and for VR-CTT vs. pen-and paper (p's<.001). A significant group x test format interaction (p<.05) was obtained for Trails B, consistent with better separation between groups for the VR format.

C. *Analysis of motor pefomrance*

Mean (±SD) for $\%D_a$ were 69.2±7.7% and 71.6±7.7% for young and middle-aged groups, respectively (p=.39). The corresponding values for $\%D_b$ were 79.5±10.7% and 86.3±11.1% (p=.02). For both groups, $\%D_b$ was significantly larger than $\%D_a$ (p<.001). Fig. 5 illustrates these findings. Each of the traces shown (A-D) is comprised of hundreds of hand trajectories (see legend for details). For Trails A, velocity profiles are generally characterized by a single peak, but trajectories for Trails B clearly deviate from this pattern.

IV. DISCUSSION

A. *General*

Our results show that the newly developed VR-CTT adapted for HMD and the traditional pen-and-paper version share similar psychometric properties (e.g., longer completion time for B vs. A). The relatively high correlations (r≈0.6) between corresponding parts suggest that the two tests measure the same cognitive constructs (e.g., sustained, divided attention). In a cross-validation study of the TMT and CTT, Dugbartey and colleagues reported comparatively lower correlation values of .35 for Trails A and .45 for Trails B [23]. Further, like the pen-and-paper test, the VR-CTT test appears to exhibit good discriminant validity in that it distinguishes among young and middle-aged healthy adults.

Consistent with our previously reported results for a VR-CTT adapted for large scale VR systems [17], completion times on the HMD VR-CTT were significantly longer than for the pen-and-paper CTT. However, completion times for the large-scale VR-CTT were even longer than those obtained here for the HMD VR-CTT. For example, for 11 participants with mean age of 37.1±14.2 y, large-scale VR-CTT Trails B completion time was 219.2±74.4 sec (as compared with 64.5±17.9 for the original pen-and-paper measure). In the present study, across 57 participants with mean age of 42.11±14.92 y, Trails B completion time for HMD VR-CTT was 134.35 ± 37.08 sec, (as compared to 74.7 ±27.6 sec for the pen and paper measure). One account for these differences in completion time between the two VR-CTT versions relates to the different levels of visual immersion. In the HMD VR-CTT, there is no visual feedback from the arms, and the participant's subjective experience of the task is solely by manipulating the avataric marker. In contrast, the large-scale VR-CTT allows the participant to view both his/her arm and the avataric marker as s/he makes reaching movements toward the virtual targets. The latter configuration may complicate sensorimotor integration given the two parallel, relevant sensory input streams (physical arm, virtual avataric marker); this hypothesis that should be further investigated. More generally, the much longer response times for the VR-CTT versions relative to the pen-and-paper CTT may reflect a larger dynamic range of performance or greater task difficulty [18].

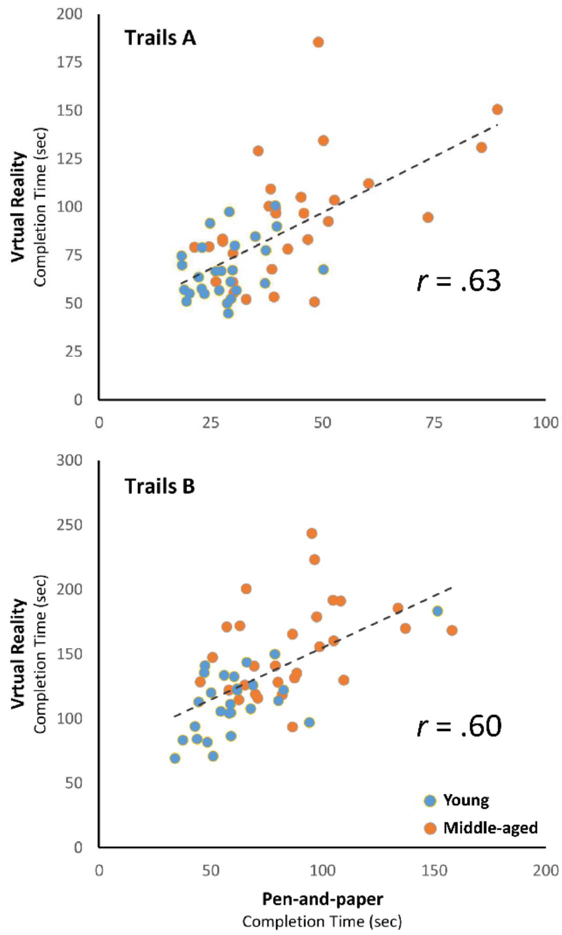

Fig. 4. Convergent construct validity of the immersive VR Color Trail-Making Test (VR-CTT). Gold standard classic pen-and-paper CTT (x-axis) and corresponding VR-CTT (y-axis) completion times for Trails A (t_a; upper panel) and Trails B (t_b; lower panel) for all 56 participants (27 young; 29 middle-aged). Regression equation for t_a: $y=1.16x+38.86$. Regression equation for t_b: $y=0.80x+74.30$. Pearson correlations are shown (p's<.001).

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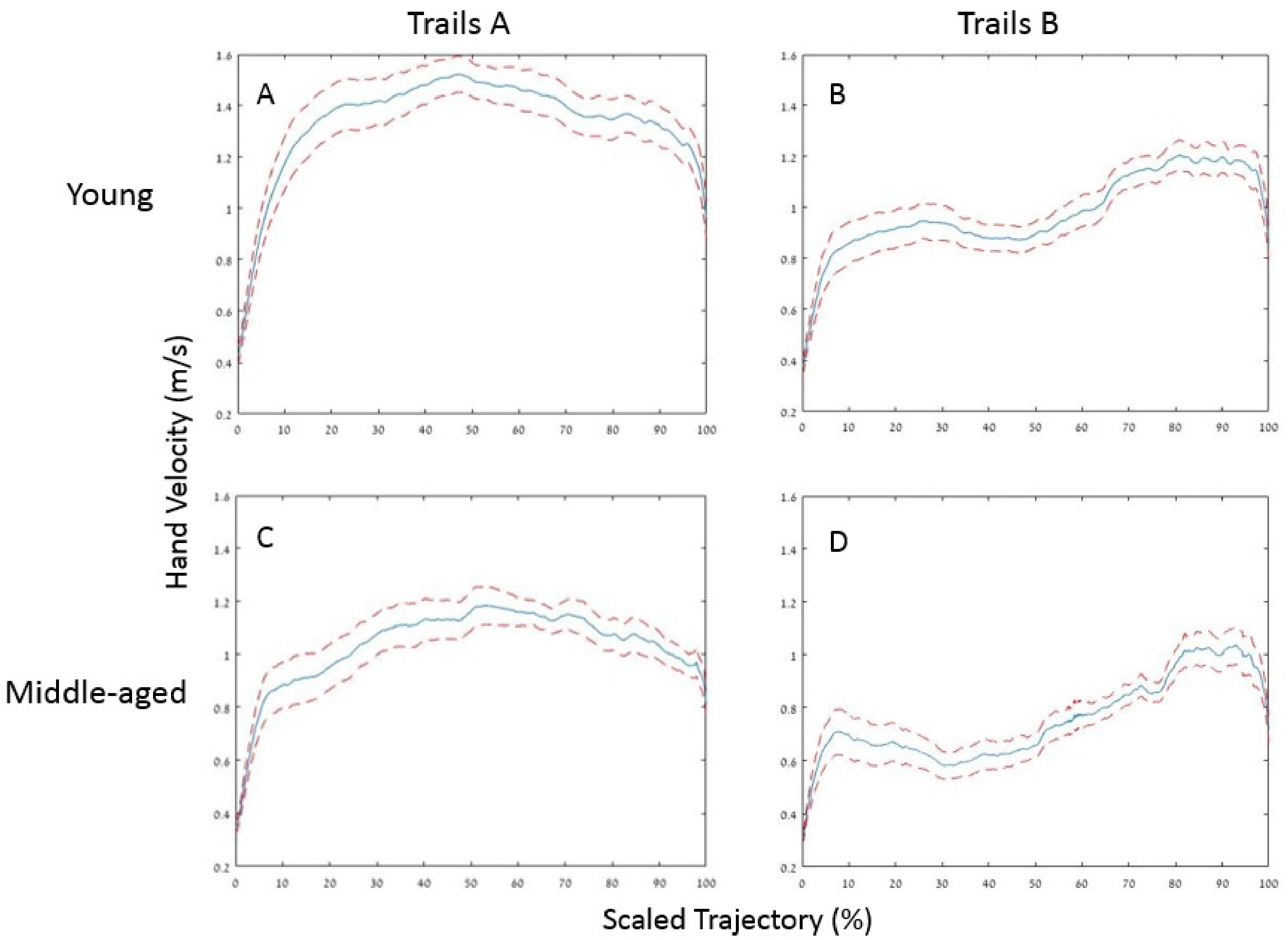

Fig 5. VR-CTT arm movement velocity profiles. Scaled (from 0 to 100%) hand trajectories for young (panels A,B) and middle-aged (panels C,D) groups for Trails A (panels A, C) and Trails B (panels B, D). The blue trace represents the averaged hand velocity profile; the dashed red lines indicate ±SD. For Trails A, data from 378 and 406 arm movements (for the selected fourteen target-to-target paths; see Methods) were averaged for the young and middle-aged groups, respectively. For Trails B, 324 and 348 arm movements (for the selected twelve paths) were averaged. It is apparent that velocities are higher for the young group. Though Trails A trajectories are characterized by a single-peak curvilinear velocity profile, Trails B velocity profiles reflect a two-phased trajectory consisting of an initial peak of moderate velocity followed by another peak resembling the single-peak profile in terms of velocity and morphology.

B. Limitations and future directions

Several technological limitations of the present HMD VR-CTT version should be noted. For example, visual acuity of the participant is more critical for performance of the VR-CTT than for the pen-and-paper version, in which the paper remains at a constant, comfortable distance at which all potential targets are visible. The 3D VR-CTT is fundamentally different in this respect, as the potential targets are located at a variety of virtual depths.

An important outcome of the present study is the methodological approach we adopted to quantify motor control interactions during executive function testing. However, our quantification method was based on a theoretical model for planar movements [20], mainly due to the absence of a reliable theoretical model for 3D hand reaching movements.

Future directions include: (1) assessment of discriminant validity in patient cohorts; (2) leveraging VR technology to create even more ecological and true-to-life VR-CTT versions; (3) adapting additional neuropsychological tests for implementation in an immersive VR environment. We believe that such neuropsychological tests are highly relevant to real-life cognitive functioning and may thus prove more clinically meaningful than traditional paper-based neuropsychological tests. To evaluate this proposal, follow-up studies must ultimately demonstrate a higher correlation between the VR adaptation and related/corresponding everyday activities than the original paper-based test.

C. Conclusion

The present work provides initial evidence of feasibility and validity of a low-cost VR version of the classic Color Trail Making Test, a traditional pen-and-paper test of sustained and divided attention. Critically, this work demonstrates the feasibility of converting a neuropsychological test from 2D to 3D (**first goal**) while preserving core features of the task and assessing the same

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cognitive functions (**second goal**). Further, VR-CTT showed the anticipated age effect differentiating middle-aged from young participants (**third goal**). Our novel findings on the relationship between classical cognitive performance and upper-limb motor planning and execution (**fourth goal**) may lead to new analysis methods for other ecological VR-based neuropsychological tests that incorporate cognitive-motor interactions.

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