Embodiment of a functionally altered virtual arm in children and adults

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Abstract

This study aimed to investigate whether human embodiment is dependent on the sensorimotor functions of one's body. We hypothesised that body function constrains both the sense of ownership and sensorimotor control of the body movements. We studied these relationships in the context of control of unilateral goal-directed forward arm reaching movements made with a virtual arm. In addition, we expected that children possess more adaptable body representations compared to adults, facilitating greater acceptance of virtual bodies with altered sensorimotor contingencies. We tested 5-7 and 8-10-year-old children, and young adults. Participants took part in an animal feeding game within a Virtual Reality environment. At each age, we manipulated the visual gain of hand movements to alter reaching functionality in three groups: compared to a normal (100%) gain, reaching arm length was slightly reduced (80%); slightly increased (120%); or greatly increased (400%). Parameters representing reach kinematics, subjective perception of arm length, and subjective limb embodiment were assessed during and after reaching with normal and altered control gain. In addition to changes in their reach kinematics, changes in subjective embodiment and reaching affordance were recorded compared to baseline reaching without altered visual gain. We found that the altered reaching functionality reduced subjective ratings of limb ownership during exposure to the 400% visual gain modification in the group of adults only. In contrast, changes in reach kinematics occurred in all the age groups of children and adults, with age group-specific adjustments in the motor control strategy, characterised by altered magnitude and spatiotemporal placement of peak velocity as well as smoothness of reaching. Finally, at all ages subjective reaching affordance estimates were enhanced following exposure to the two functionality conditions with increased arm length. Our results indicate that the sense of ownership, accuracy of body representations, and characteristics of sensorimotor control are related to bodily function. In addition, it appears that these relationships might be more plastic, or perhaps more tolerant to functional alterations in terms of perceived ownership, in children compared to adults.

Introduction

Our physical and sensorimotor abilities are a highly skilled, evolved system which allow us to use our body to interact in a highly adapted manner within our environment. Naturally, our bodies are also subject to physical limitations. However, recent technological advances allow users to experience augmented bodies. These may be *functionally* different to one's own - able to reach further, exert greater force, or even fly through virtual space. This raises several related questions: first, what the outer limits are of what we can accept as our own body? Second, how does body function determine the user's control of the body and their feeling of ownership over it? An important case of augmentation is virtual bodies, which can be used in experiences focused on education (Bailey & Bailenson, 2017), entertainment, and therapy (Won et al., 2017). In this study we ask how users can learn to control and accept ('embody') altered virtual bodies, focusing on how the functionality of a virtual limb may limit its embodiment. We explore this not only in adults, but also in children, whose high levels of neural plasticity and over-reliance on visual signals for locating their own body (Cowie et al., 2013) make them a key group for mapping the outer limits of body augmentation.

Understanding one's own physical body arises from a complex interaction of multisensory signals and prior expectations. In this intricate system, there is some plasticity in what we can accept as our own body. For example, a spatially displaced, plaster-cast rubber hand which is stimulated at the same time as our own can elicit subjective feelings of 'ownership' (Botvinick & Cohen, 1998; Gonzalez-Franco & Peck, 2018), with corresponding neural activity (Ehrsson, 2007) and a drift in perceived own-hand position. Such bodily illusions can be maintained for fake hands which differ in texture (Preston & Kirk, 2022) or size (Cowie et al., 2022; Pavani & Zampini, 2007): therefore, there is plasticity in these aspects of own-body representation. Supernumerary body parts such as an extra thumb (Kieliba et al., 2021) or virtual third arm (Guterstam et al., 2011) can also be integrated into the functional repertoire and experienced as part of one's own body. Bodily illusions can be especially powerful in children under 10 years, who appear to more be 'visually captured' by fake hands (Allen et al., 2023; Cowie et al., 2018; Cowie et al., 2016; Dewe et al., 2022; Gottwald et al., 2021). Coupled with the substantial bodily growth at this age, this work suggests high levels of plasticity in own-body representation in children under the age of 10 years. In sum, it is clear that the self-other distinction at the core of our experience, memory, and identity can be manipulated – including in new digital contexts like virtual reality, and especially in children.

However, it is also clear that there are limits on what we can accept as part of our own body. In comparison with a hand-like form, illusions of ownership are drastically reduced for a wooden block (Tessari et al., 2010), misoriented hand (Costantini & Haggard, 2007), or abstract virtual shape (Ferran Argelaguet et al., 2016; Lenggenhager et al., 2007). After years of use, a prosthetic is still not represented in the same way as a real hand (Maimon-Mor & Makin, 2020). In broad terms, these limits on plasticity can be explained by supposing that novel body parts which differ greatly from one's own original configuration make unreasonable demands on cognitive, attentional, and/or neural mechanisms (Makin et al., 2017), resulting in a rejection of the novel body part through a series of hierarchical comparisons between the original and novel bodies (Tsakiris, 2010), or in more recent formulations a dynamic set of constraints within a probabilistic framework (Apps & Tsakiris, 2014; Chancel et al., 2022). As well as plasticity, therefore, there are also clear *limits* on body representation.

What is not clear from extant work is which dimensions these limits might operate on. Posture is certainly one: minor discrepancies between felt and seen hand postures can severely disrupt bodily illusions, including for children (Gottwald et al., 2021; Tsakiris & Haggard, 2005). The dimension often referred to as 'form' or 'corporeality' is less well specified. Compared with a normal hand, embodiment is reduced for a wooden block (Tsakiris et al., 2010) or moving hand with missing fingers (Schwind et al., 2017), yet users can accept a third arm (A. S. Won et al., 2015), or lobster body (Andrea Stevenson Won et al., 2015). We propose that a key, under-studied dimension which may explain these seemingly incoherent findings is body functionality (Aymerich-Franch & Ganesh, 2016; Aymerich-Franch et al., 2016; Makin et al., 2017). Perhaps our ability to embody an object depends on how well it allows us to achieve a functional end or goal. Arguably, participants may fail a block, hand with missing fingers, or heavy prosthesis not because of its superficial appearance but because of its reduced function. Conversely, an augmented body which offers enhanced function - like a third arm - may be accepted. Indeed, for this reason tools may be accepted into the motor schema (Cardinali et al., 2009) or even elicit some affective experience of ownership (Cardinali et al., 2021). However, to fully determine whether function is an important dimension on which to consider embodiment, we must isolate and experimentally manipulate it.

In the current study, we used a modified 'GoGo' technique (Poupyrev et al., 1996) to alter the function of a moving virtual arm. Visual gain was manipulated so that the virtual arm was made to extend far into space or perform shortened reaches. Crucially, we could therefore either reduce or increase its functionality, and indeed we could vary this parametrically. In an 'increased function' condition, a reach in real space resulted in an extended reach for the virtual arm: the visual gain between the participant's reach and the virtual arm reach was greater than one. In a 'reduced function' condition, a reach in real space resulted in a shorter reach for the virtual arm: the visual gain between the participant's reach and the virtual arm reach was below one. To determine how embodiment depends on arm functionality, we compared baseline experience of virtual reaching with several between-subjects conditions: a reduced-function arm with visual gain of 0.8 ('F-'), an increased-function arm with visual gain of 1.2 ('F+'), and an increased-function arm with visual gain of 4.0 ('F++'). The F- and F+ conditions were symmetrical about 1, allowing for a direct comparison of reduced and increased function, while the F+ and F++ conditions compared different degrees of enhanced function. We explored the upper limits of plasticity using the F++ condition; and by testing not only adults, but also children who, as explained above, might possess more plastic body representations. We studied both younger children (5-7 years) for whom reaching is more ballistic and older children (8-10 years) who are better able to integrate sensory feedback for motor control (Hay, 1990).

We tested how the arm's functionality constrained the user's embodiment of it using multiple embodiment indices. Subjective experience was measured through questionnaire, and perception of own-body functionality through reaching affordance thresholds (L. P. Lin et al., 2020). Incorporation of the novel body part into a motor schema was measured through several kinematic indices of visuomotor control: peak velocity and the temporal and spatial position of this peak (Schmidt, 1975), and reach smoothness. A reach can be subdivided into two phases either side of a velocity peak: an "approach" phase containing a preplanned, accelerating movement towards a target and a "homing-in" phase of feedback-driven deceleration and online control (Georgopoulos, 1986; Jeannerod, 1988). Peak velocity itself would typically increase with target distance, while its spatial and temporal position can be considered an expression of a specific reach solution (Jakobson & Goodale, 1991): an earlier peak prioritises accuracy through a longer deceleration phase, while a later peak facilitates speed (Peternel et

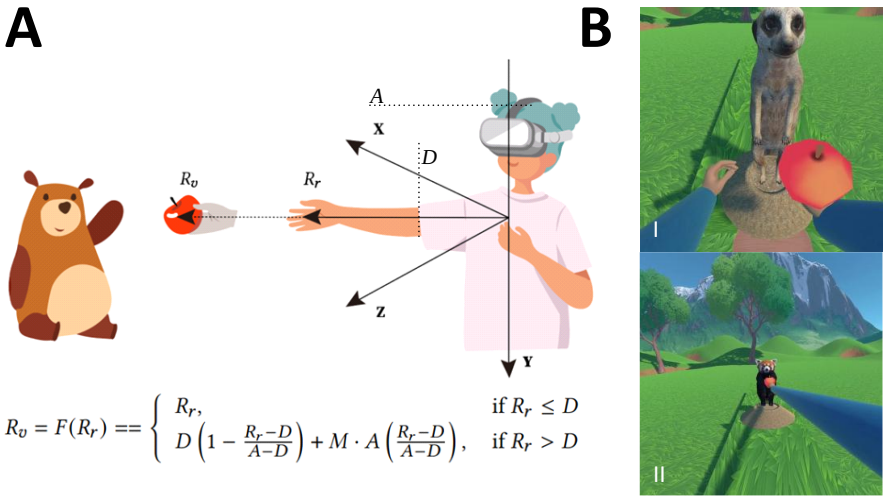
al., 2017; Plamondon & Alimi, 1997). Within a single context, the *relative* timing or position of the velocity peak (e.g. 50% reach time) is expected to be invariant, scaling to fit the current target distance (MacKenzie et al., 1987; Schmidt, 2003).

We hypothesized that increased-function bodies would elicit ownership, but less so than typical bodies, and that reduced-function bodies would be more difficult to embody than increased-function bodies. We expected the novel body to affect the perception of own-body functionality (perception of increased reach affordance following an increased-function virtual experience). We hypothesised that sensorimotor control of the body would be adaptable to a great variety of functional alterations including extreme functional change (e.g. F++ condition): in such cases one would expect to observe context-specific adjustments in the sensorimotor control regime. Finally, we hypothesised that plasticity would be greatest in children, as evidenced by greater embodiment, better-adapted reaches, and stronger after-effects on perceived own-body function.

Results

Participants completed an animal-feeding reaching task within an immersive virtual environment (Fig. 1, Fig. S1). Each participant completed a baseline block of reaches in which the virtual arm extended as the real arm, followed by an experimental 'GoGo' block where the arm's function changed: the ratio of virtual arm: real arm length gradually tended towards an extreme of 0.8 (F-), 1.2 (F+), or 4.0 (F++).

Figure 1. A.) a relationship between real (Rr) and virtual (Rv) hand position: an inflection point (D) at 2/3 arm length (A) was chosen as a comfortable distance for a transition between normal and altered functionality. As the real arm extended further than D (R*r*>D), the virtual arm length began to change in linear proportion to the real distance travelled. The maximum was a multiple, M, of the arm length: in the F- condition M=0.8; F+ M=1.2; F++ M=4.0. B.) Illustrations of the reaching sequence for a normal (I) and a F++ (II) reach: moving into a ready volume triggers the appearance of a food item, grasping the food item triggers onset of a target animal, the forward reach is performed and the food item released, the animal nibbles the food item and disappears.



Each of 259 participants experienced only one altered function condition. Age groups were young children (5-8 years), older children (8-11 years), and adults. Reaches were always made to four distances: two before the inflection point, at 52 and 64% of each participant's arm length; and two after the inflection point, at 88 and 100%. The actual reaching movements required to reach targets were therefore constant across baseline and GoGo blocks. However, the same reach would appear further in virtual space for F+ and F++ conditions and nearer for F-. Experimental factors were therefore Age (young children, older children, adults), Functionality (F-, F+, F++), Block (baseline, GoGo), and Distance (52, 64, 88,100% arm length). During all reaches, movement was measured using the HMD's inbuilt tracking mechanism, from which we extracted kinematic variables of interest. After each block, reaching affordance was measured in a new virtual environment in which, without reaching, they made a Y/N verbal judgment on whether they could reach an apple on a table in front of them. Using repeated trials in a psychophysical staircase procedure where the apple's distance was varied, we measured the threshold at which they judged that they could just reach the apple. Finally, participants answered questions on user experience, perceived ownership and agency over the virtual arm, and the extent to which it felt tool-like; and completed a control statement to assess suggestibility. ANOVA with factors above was used to analyse the dependent variables: Table 1 summarizes the significant effects and interactions for each performance parameter. For clarity, non-significant results are not shown.

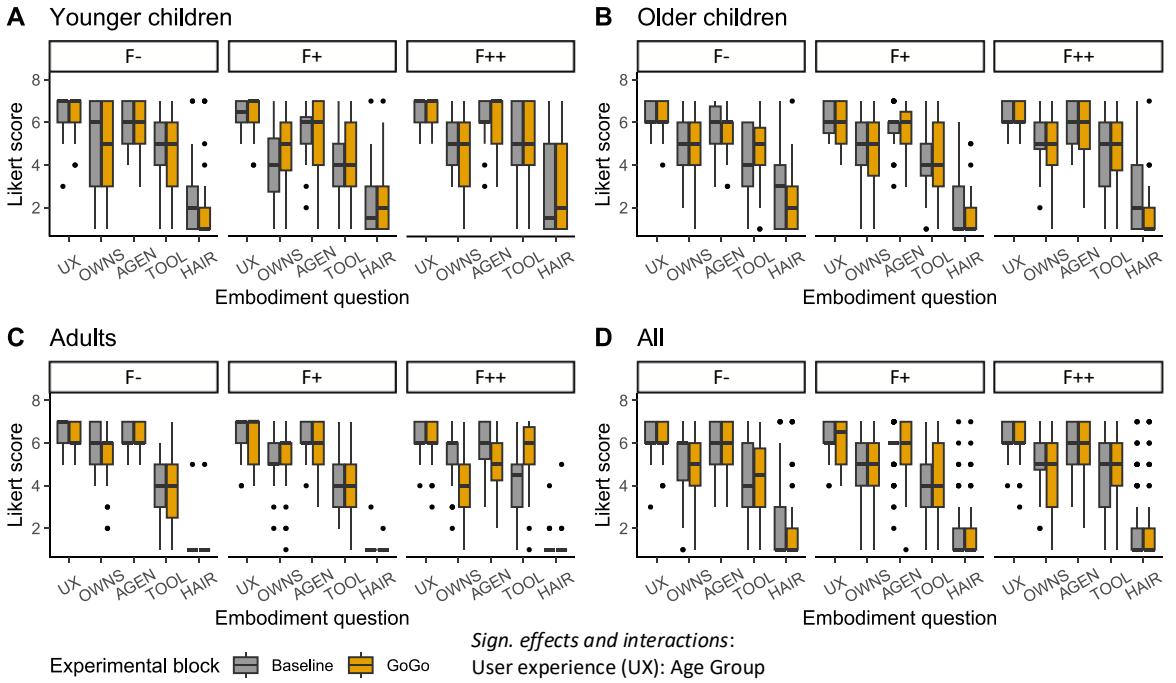
Table 1. Overview of significant effects and interactions by performance parameter. Age: Age Group; Funct.: Functionality; Dist.: Target Distance.

	Main effect / interaction (df treat, df res)														
	Age	Funct.	Age * Funct.	Block	Age * Block	Funct. * Block	Age * Funct. * Block	Dist.	Age * Dist.	Funct. * Dist.	Age * Funct. * Dist.	Block * Dist.	Age * Block * Dist.	Funct. * Block * Dist.	Age * Funct. * Block * Dist.
Parameter															
User Experience	F(2,500)= 4.82, p=0.008, $p\eta^2$=0.02														
Ownership		F(2,500)= 3.45, p=0.03, $p\eta^2$=0.01	F(4,500)= 4.09, p=0.003, $p\eta^2$=0.03		F(2,500)= 4.03,p=0.02, $p\eta^2$=0.02	F(2,500) =4.46, p=0.01, $p\eta^2$=0.02									
Agency			F(4,500)=3.59, p=0.007, $p\eta^2$=0.03	F(1,500)= 8.67,p=0.003, $p\eta^2$=0.02											
Tool Quality		F(2,500)= 5.70, p=0.004, $p\eta^2$=0.02													
Suggestion	F(2, 500)= 90.13,	F(2,500)= 4.33, p=0.01, $p\eta^2$=0.02	F(4,500)= 3.53, p=0.007, $p\eta^2$=0.03	F(1,500)= 10.21, p=0.001, $p\eta^2$=0.02	F(2,500)= 6.26, p=0.002, $p\eta^2$=0.02	F(2,500) =4.29, p= 0.01, $p\eta^2$ 0.02	F(4,500)= 2.51, p=0.04, $p\eta^2$=0.02								

	$p<0.001$, $p\eta^2= 0.26$											
Peak Velocity	$F(2,250)=17.17$, $p<0.001$, $p\eta^2=0.12$		$F(1,250)=6.56$, $p= 0.01$, $p\eta^2=0.03$	$F(2,250)=6.26$, $p=0.002$, $p\eta^2=0.05$			$F(3,750)=196.76$, $p<0.001$, $p\eta^2=0.44$	$F(6,750)=15.06$, $p<0.001$, $p\eta^2=0.11$	$F(6,750)=7.30$, $p<0.001$, $p\eta^2=0.06$	$F(3,750)=6.69$, $p<0.001$, $p\eta^2=0.03$	$F(6,750)=13.51$, $p<0.001$, $p\eta^2=0.10$	
Relative Time To Peak Velocity	$F(2,250)=7.29$, $p<0.001$, $p\eta^2=0.06$				$F(2,250)=4.58$, $p=0.01$, $p\eta^2=0.04$	$F(4,250)=3.14$, $p=0.02$, $p\eta^2=0.05$	$F(3,750)=7.61$, $p<0.001$, $p\eta^2=0.03$	$F(6,750)=4.29$, $p<0.001$, $p\eta^2=0.03$		$F(3,750)=3.11$, $p= 0.03$, $p\eta^2=0.01$		
Relative Distance To Peak Velocity	$F(2,250)=45.36$, $p<0.001$, $p\eta^2=0.27$					$F(4,250)=2.48$, $p=0.04$, $p\eta^2=0.04$	$F(3,750)=107.08$, $p<0.001$, $p\eta^2=0.30$	$F(6,750)=13.67$, $p<0.001$, $p\eta^2=0.10$				$F(12,750)=2.71$, $p= 0.001$, $p\eta^2=0.04$
Smoothness	$F(2,250)=66.98$, $p<0.001$, $p\eta^2=0.35$	$F(2,250)=3.92$, $p=0.02$, $p\eta^2=0.03$	$F(1,250)=9.15$, $p=0.003$, $p\eta^2=0.04$		$F(2,250)=19.50$, $p<0.001$, $p\eta^2=0.13$	$F(4,250)=2.87$, $p=0.03$, $p\eta^2=0.04$	$F(3,750)=13.99$, $p<0.001$, $p\eta^2=0.05$		$F(6,750)=4.07$, $p<0.001$, $p\eta^2=0.03$	$F(3,750)=8.51$, $p<0.001$, $p\eta^2=0.03$	$F(6,750)=4.47$, $p<0.001$, $p\eta^2=0.03$	
Reaching Affordance	$F(2,249)=27.08$, $p<0.001$, $p\eta^2=0.18$		$F(1,249)=27.75$, $p<0.001$, $p\eta^2=0.10$		$F(2,249)=6.42$, $p=0.002$, $p\eta^2=0.05$							

Subjective embodiment

Figure 2. Boxplots for subjective embodiment ratings as a function of age group, functionality group and block: A) younger children, B) older children, C) adults, D) all three age groups. F-: reduced function; F+: increased function; F++: strongly increased function. UX: user experience; OWNS: sense of ownership; AGEN: sense of agency: TOOL: sense of tool-likeness; HAIR: suggestibility control.



Sign. effects and interactions:
User experience (UX): Age Group
Ownership (OWNS): Functionality, Age Group*Functionality, Age Group*Block, Functionality*Block
Agency (AGEN): Age Group*Functionality, Block
Tool interpretation (TOOL): Functionality
Suggestion (HAIR): Age Group, Functionality, Age Group*Functionality, Block, Age Group*Block, Functionality*Block, Age Group*Functionality*Block

We highlight key findings for each of the five Likert scale questionnaire items (Figure 2). First, the functionality of the virtual arm affected the participant's feeling of ownership over it. This is shown in a significant interaction between functionality group and block, where only the F++ group reported reduced ownership after the GoGo block ($t(500)=2.7$, $p=0.007$; Fig. 2d; other groups both $t(500)<1.26$, $p>0.21$). Therefore, while ownership is possible for arms with mildly reduced or mildly enhanced function, it is compromised by highly increased function. Second, age affected ownership of the GoGo arm. Age effects were examined with Post-hoc comparisons on the significant interaction (Table 1) between age group and block. The GoGo experience reduced ownership for adults ($t(500)=3.83$, $p=0.0001$) but not for children (both groups $t(500)<1.42$, $p>0.16$), Fig. 2c). Further, adults, but not children, gave lower ratings in the F++ group than in the F- ($t(500)=4.34$, $p<0.001$) and F+ ($t(500)=2.83$, $p=0.005$) groups. We therefore suggest (Fig. 2c) that overall, the limiting effects of function on ownership were most pronounced for adults.

While ownership was reduced only in the F++ group, the sense of agency was slightly reduced across all GoGo conditions (mean=5.60, SD 1.27; $t(500)=2.94$, $p=0.003$) compared to baseline (mean=5.95, SD 0.98). (Additional effects of age independent of block are reported in

supplementary materials). Suggestibility ratings (agreement that a participant's hair turned blue) were overall low. An unexpected 4-way interaction (Table 1) was caused by older children in the F++ group reducing their ratings ($t(500)=2.05$, $p=0.04$). As predicted, suggestibility ratings were lower in adults (mean=1.13, SD 0.60) than in children (younger: mean=2.50, SD 2.0; older mean=2.14, SD 1.49; both $t(500)>10.34$, both $p<0.0001$; Fig. 2). This small bias does not weaken the interpretation of the other questionnaire items above, which are not main effects of age. Likewise, we note that children did not simply give high scores across the board, but moderated their answers across questions and conditions, e.g. giving lower scores for ownership than for agency.

Several additional measures were taken to help contextualise the experience. Participants in the F++ groups rated the virtual limbs more as resembling a tool (mean=4.79, SD 1.69) than the F- (mean=4.26, SD 1.69; $t(500)=2.88$, $p=0.004$) or F+ (mean=4.32, SD 1.64; $t(500)=2.97$, $p=0.003$) groups. Regarding user experience, younger children (mean=6.35, SD 0.89) and adults (mean=6.24, SD 0.89) rated the game slightly more favourably than older children (mean=6.12, SD 0.78), who were most familiar with videogame technology (mean usage for younger children: 7.2 h/wk, SD 7.2; older children: 9.4 h/wk, SD 8.0; adults: 4.8 h/wk, SD 8.2).

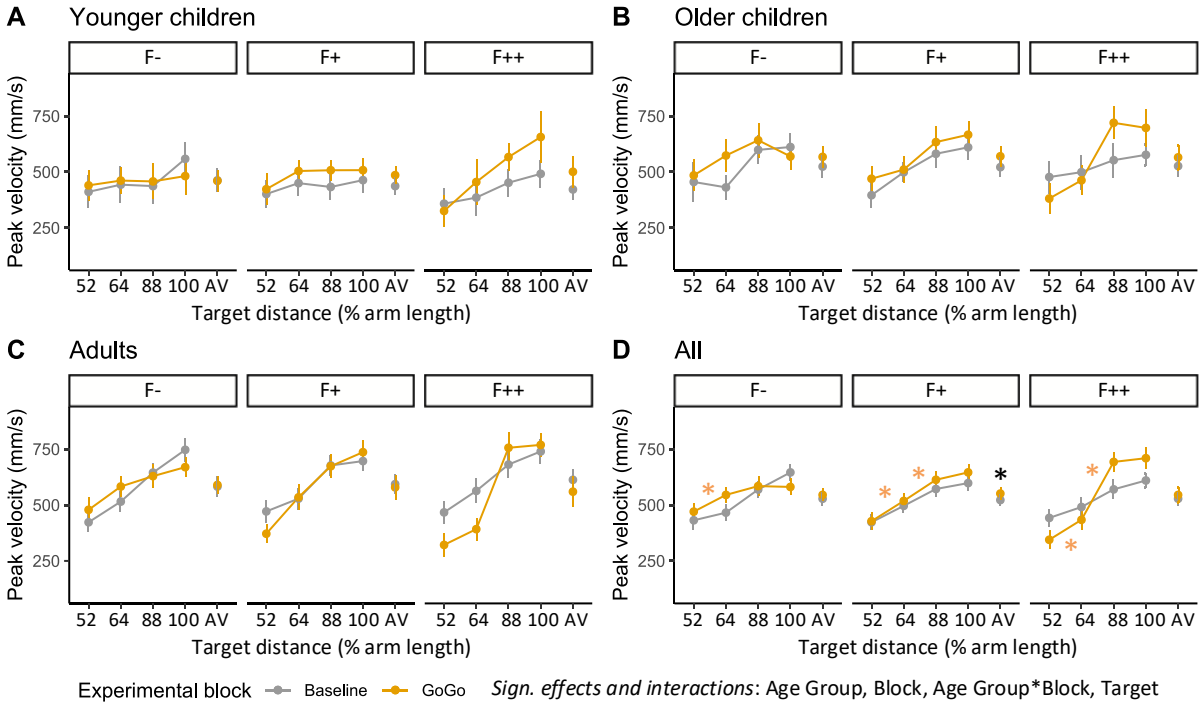
Motor control

Peak velocity

Suggestive of a well-calibrated reaching movement, the peak velocity achieved during the movement increased with target distance condition (52% target distance: mean=420 mm/s, 64% TD: mean=488 mm/s, 88% TD: mean=591 mm/s, 100% TD: mean=625 mm/s). The effects of target distance on peak velocity grew stronger with age (age by distance interaction, Table 1): this is explored further in analysis below.

The GoGo experience elicited new motor solutions. There was an overall increase in peak velocity for older children (age by block interaction, baseline: mean=523, SD 142; GoGo: mean=566, SD 155; $t(250)=3.23$, $p=0.02$; Fig 3b). Across groups, GoGo changed the scaling of velocity to target distance (Fig. 3d; Table 1). A 3-way interaction showed that in the GoGo block, calibration was altered in the F- group ($F(3,249)=8.99$, $p<0.001$, $p\eta^2=0.10$), and F++ groups ($F(3,252)=18.18$, $p<0.001$, $p\eta^2=0.18$; full statistics in supplementary materials; asterisks indicate significant differences in Fig. 3).

Figure 3. Peak velocity as a function of age group, functionality group, block, and target distance condition: A) younger children, B) older children, C) adults, D) all three age groups. F-: reduced function; F+: increased function; F++: strongly increased function. Error bars show the confidence interval. Asterisks indicate statistically significant single comparisons ($p< 0.05$). Significant interactions were followed up with Post-hoc comparisons: asterisks between two neighbouring target distances indicate a significant difference between them (black: irrespective of block; grey: for baseline only; orange: for GoGo only). Asterisks above a specific target distance indicate a main effect of block for that target.

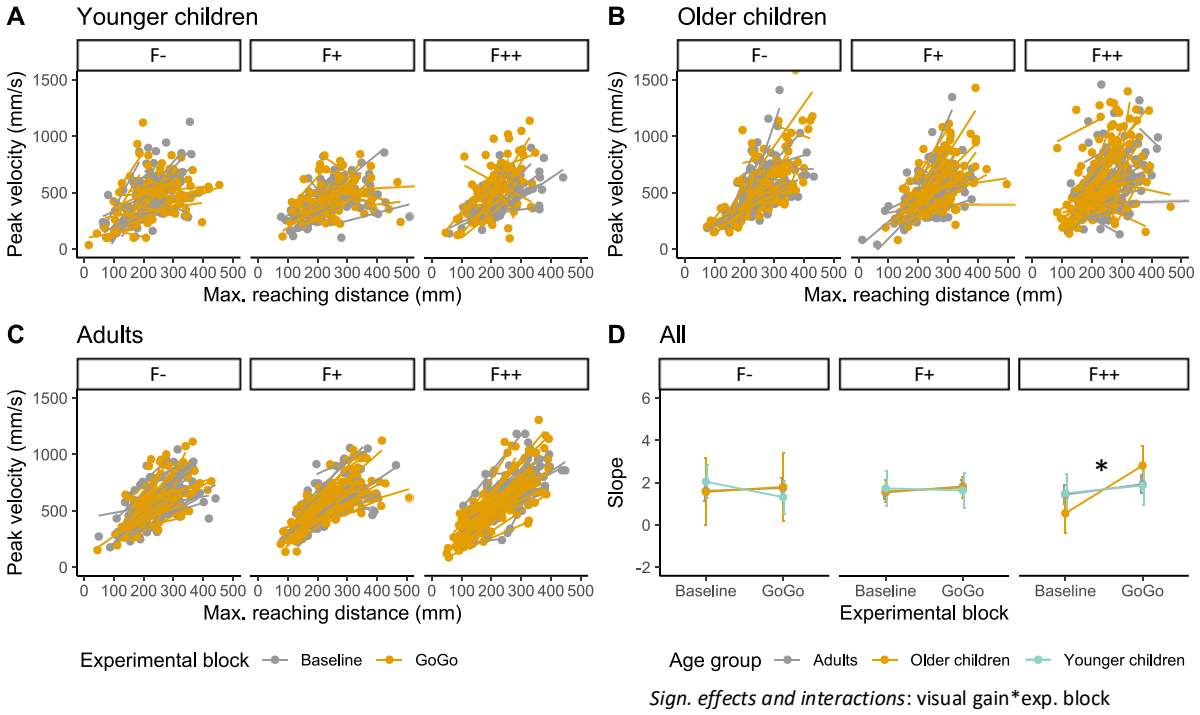


Sign. effects and interactions: Age Group, Block, Age Group*Block, Target Distance, Age Group*Target Distance, Functionality*Target Distance, Block*Target Distance, Functionality*Block*Target Distance

To explore these findings, we assumed that participants followed a unitary visuomotor control scheme across the four target distances (a fixed relationship between the distance of a planned reach and its peak velocity). We tested whether this might hold across ages and conditions. To do this we accounted for the fact that adults made physically longer reaches because of their longer arms, performing for each participant linear regression analyses of peak velocity *as a function of reach distance*, where equal regression slopes would indicate the same control scheme. There was no age effect, suggesting that adults and children indeed adopted similar control schemes. (This suggests that the distance by age interaction reported in the ANOVA above resulted partly from adults with longer arms reaching further distances & peak velocities.)

However, independent of age (Fig. 4d), these slopes showed an interaction between functionality group and block ($F(2,250)=3.18$, $p=0.04$, $p\eta^2= 0.02$): in the F++ groups only, the slope was greater in the GoGo block than at baseline ($t(250)=3.01$, $p=0.03$; Fig. 4d). Across ages, therefore, we suggest that participants applied a unitary control scheme across baseline, F-, and F+. This suggests that the differences of slope between baseline and GoGo F- reported in the ANOVA above do not hold in this more granular analysis. Most notably, it shows that in the highly functionally enhanced F++ condition participants employed a different scheme with amplified peak velocity.

Figure 4. The slope of the linear relationship between peak velocity and physical peak reaching distance as a function of visual gain group and experimental block: A) younger children, B) older children, C) adults, D) all three age groups. F-: reduced function; F+: increased function; F++: enhanced increased function. Error bars show the confidence interval. Asterisks indicate statistically significant single comparisons ($p<0.05$). Significant interactions were followed up with Post-hoc comparisons: asterisks between two target distances indicate a significant difference between neighbouring target distances (black: irrespective of block).

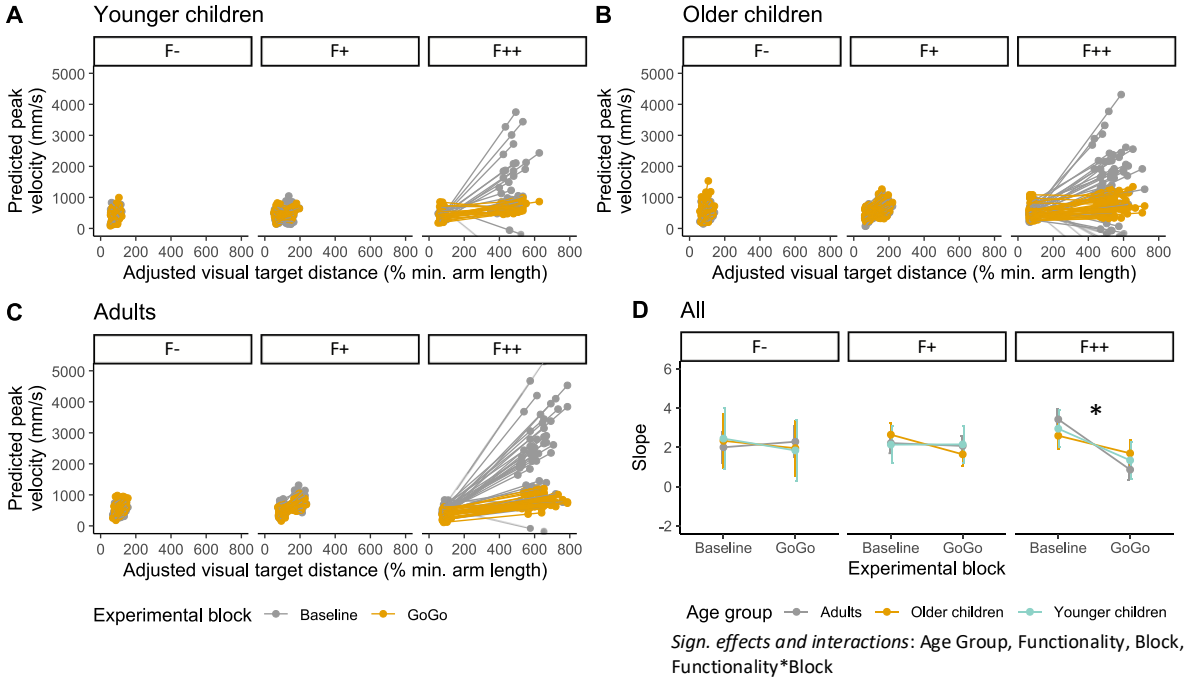


We next noted that the since the *visual distance* at which the target animals were presented was scaled to arm length, adults reached for visually further targets. This is therefore a potential confounding factor regarding age differences. We therefore performed a set of linear regressions of peak velocity *as a function of the visual distance of targets* (supplementary materials). If peak velocity calibration as a function of the perceived visual distance was maintained across ages and conditions, the regression slopes would be equal. However, they were different between the age groups ($F(2,250)=10.52$, $p<0.001$, $p\eta^2=0.08$; Fig. 5) with adults (mean=3.04, SD 2.54) showing steeper slopes than older children (mean=2.08, SD 2.54; $t(250)=2.60$, $p=0.03$) and younger children (mean=1.18, SD 2.54; $t(250)=4.57$, $p<0.001$). Adults therefore increased peak velocity more for *visually far* targets than the children. While being a general property of their reaches in the virtual environment, this does not reflect their specific adaptation to altered-function arms.

Focusing specifically on effects of function, the regression slopes on visual distance showed effects of functionality group ($F(2,250)=5.12$, $p<0.001$, $p\eta^2=0.04$) and block ($F(1,250)=12.97$, $p<0.001$, $p\eta^2=0.05$) as well as an interaction between these factors ($F(2,250)=4.72$, $p=0.01$, $p<0.001$, $p\eta^2=0.04$). Specifically, the GoGo block in the F++ condition had a lower slope (mean=0.65, SD 3.36) than baseline (mean=2.34, SD 2.83; $t(250)=4.55$, $p<0.001$; Fig. 5d). Therefore, while in the F++ condition participants adopted higher peak velocities as reaching distance increased (Fig 3d) because they calibrated reaches based on visual target distance, they did not ramp up velocity in an unrestricted fashion, achieving extremely high speeds for 400% arm length virtual targets in the F++ condition. Rather, they allowed proprioception of the real arm to moderate their movements even as they responded to the visual pull of the virtual targets and extended arm.

Figure 5. The slope of the linear relationship between peak velocity and normalized perceived visual target distance as a function of visual gain group and experimental block. Two targets were located close to participants and two targets more distant. Panels A, B, and C contrast the

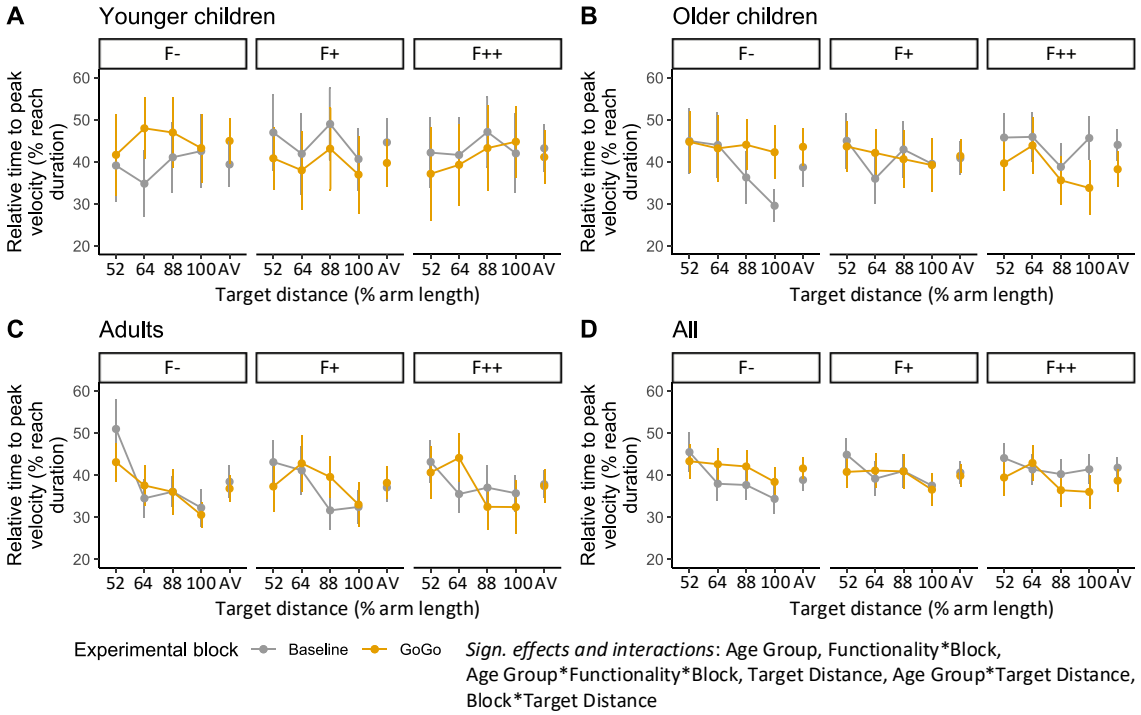
predictions of the linear regression model for the peak velocities observed in the GoGo block (orange) against the peak velocities predicted in the GoGo block by the linear regression model based on the observed performance in the baseline block (grey): A) younger children, B) older children, C) adults, D) all three age groups. It is obvious that in the F++ GoGo condition, peak velocities are not approaching the peak velocities predicted by the baseline relationship. F-: reduced function; F+: increased function; F++: enhanced increased function. Error bars show the confidence interval. Significant interactions were followed up with Post-hoc comparisons: asterisks indicate statistically significant single comparisons (p<0.05).



Relative time to peak velocity (rTPV)

The temporal proportion of the reach before peak velocity (rTPV) was, overall, calibrated to target distance (table 2; Fig 6). However, ANOVAs to resolve the interaction between age and target distance showed that younger children ($F(3,201)=1.31$, $p=0.27$, $p\eta^2=0.02$; BF=0.04) held rTPV constant. In contrast, older children ($F(3,294)=4.02$, $p=0.008$, $p\eta^2=0.04$; BF=0.66) and adults ($F(3,255)=19.45$, $p<0.001$, $p\eta^2=0.19$; BF>100), reduced rTPV with increasing target distance (Fig. 6). In fact (supplementary material), adults and by tendency older children held *absolute* timing constant, which resulted in the observed reductions in *relative* timing. This feature of children's reaching in the virtual environment was maintained across baseline and Gogo blocks.

Figure 6. Relative time to peak velocity as a function of age group, functionality group, block, and target distance condition: A) younger children, B) older children, C) adults, D) all three age groups. F-: reduced function; F+: increased function; F++: enhanced increased function. Error bars show the confidence interval.



Leaving aside target distance, rTPV showed an interaction between age group, functionality group and block (Table 1; Fig. 6a-c). The parameter was adjusted more to altered functionality by children (change from baseline in younger children: F-=5.6 %, SD 15.9; F+=-4.9 %, SD 16.7; F++=-2.1 %, SD 12.2; change from baseline in older children: F-=4.9 %, SD 12.3, F+=0.5 %, SD 12,6; F++=-5.8 %, SD 13.7) than by adults (change from baseline: F-=-1.6 %, SD 9.9; F+=1.1 %, SD 8.7; F++=-0.4 %, SD 10.2). They adopted a longer acceleration period when functionality was reduced and a more cautious, shorter acceleration period when it was increased. In the F++ condition, the TPV was particularly shortened by older children (-5.8%) compared with younger (-2.1%). Adults, on the other hand seemed to be less affected by changes in functionality. Children therefore showed more sensitivity to the intricacies of the functional context by generating a specific solution, while in contrast adults adopted a more uniform solution.

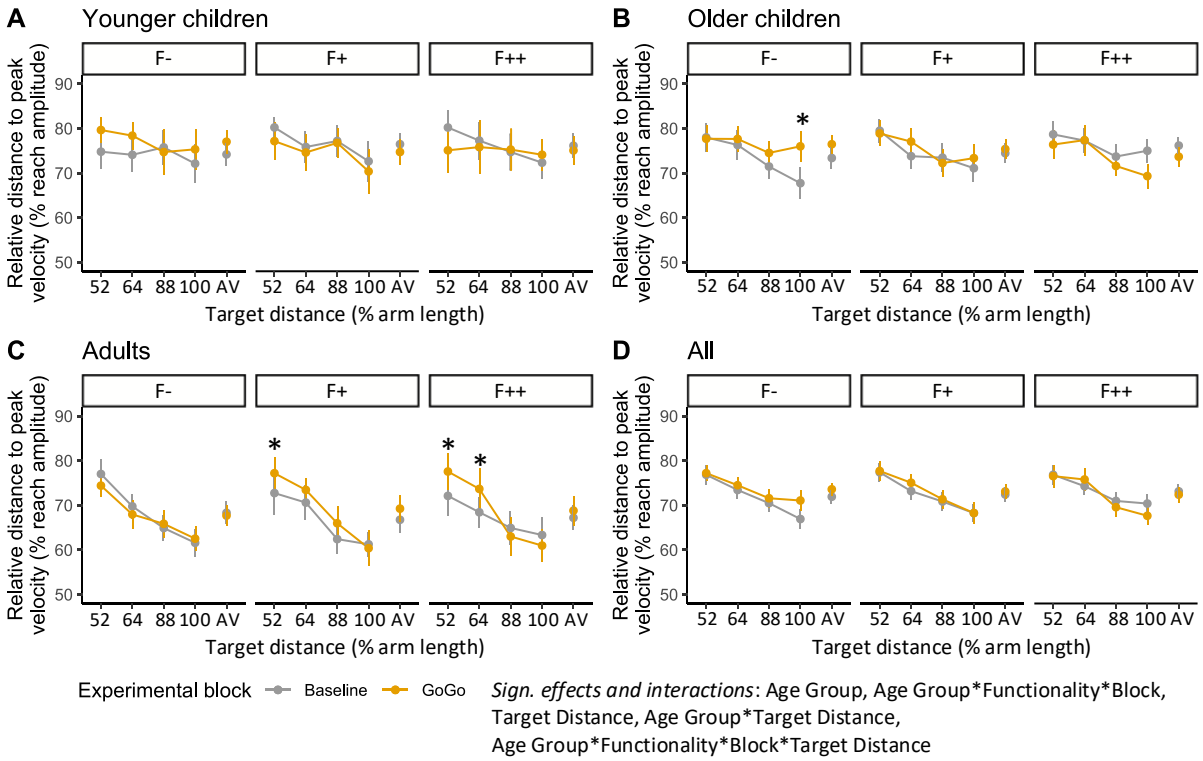
Relative distance to peak velocity (rDPV)

The *spatial* proportion of the reach spent in acceleration (rDPV) reduced for distant targets (Table 1, Fig 7). Unlike rTPV, this did not occur because participants held the *absolute* position constant (Supplementary materials). Rather, participants adopted a 'mixed' control solution, peaking somewhat further forward in absolute terms, but not so far as to keep the proportion constant across all target distances.

This pattern was stronger in adults than in children. Adults demonstrated clear decreases in rDPV across target distances, which became prominent with increased functionality. For children - especially younger children – this parameter was less sensitive to altered functionality. Statistically, this is revealed as the four-way interaction between all factors (table 2). Follow-up analyses (Supplementary matrials) indicated that while younger children showed a reduced rDPV for increasing target distances ($F(3,201)=8.10$, $p<0.001$, $p\eta^2= 0.11$; Fig. 7a), both older groups showed an interaction between functionality group, block and target distance

(Older children: $F(6,294)=2.90$, $p=0.009$, $p\eta^2=0.06$; Adults: $F(6,255)=3.90$, $p<0.001$, $p\eta^2=0.08$). These trends were stronger in all adult groups (Fig. 7c), we suggest due to a tendency to adopt later peaks even for near targets, with adults again appearing to overgeneralise from the later, altered part of the reach to the early portion.

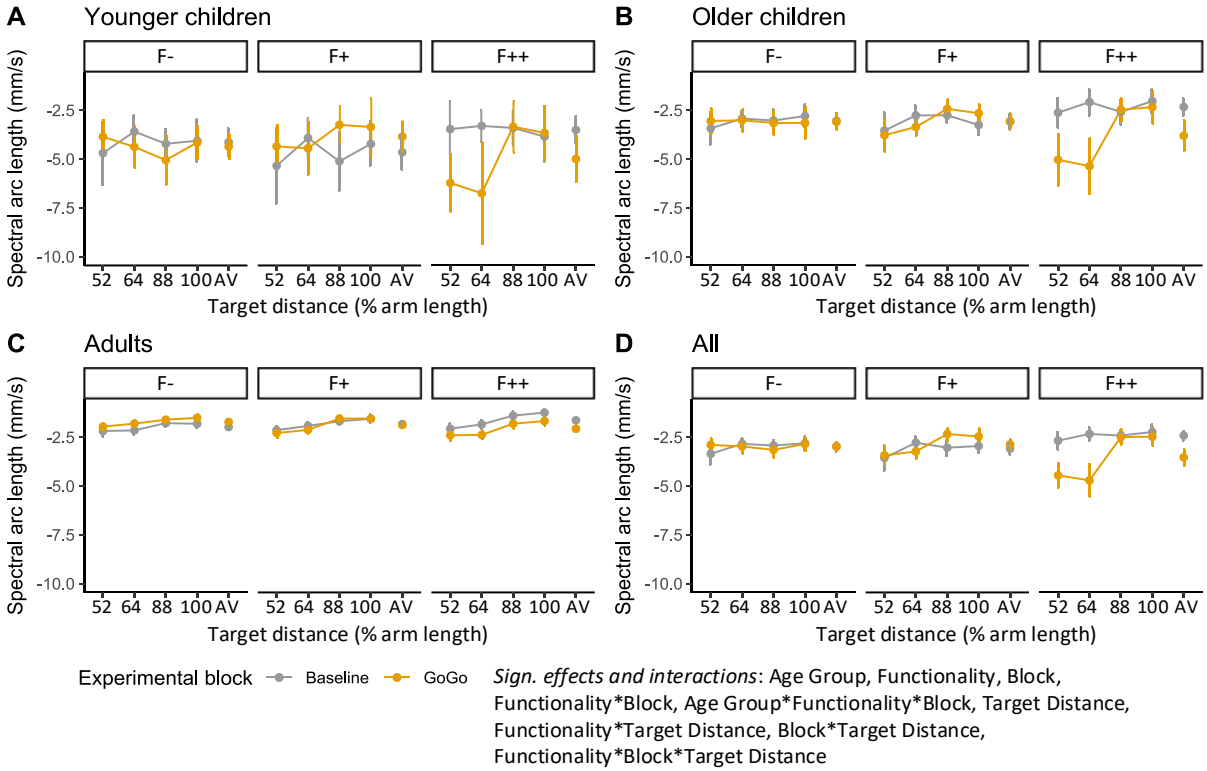
Figure 7. Relative distance to peak velocity as a function of age group, functionality group, block, and target distance condition: A) younger children, B) older children, C) adults, D) all three age groups. Significant interactions were followed up with Post-hoc comparisons: asterisks indicate statistically significant single comparisons ($p<0.05$). Asterisks above a specific target distance indicate a main effect of block.



Smoothness

Smoothness showed an interaction between age group, functionality group, block, and target distance condition (Fig. 8a-c). Separate ANOVAs showed in each age group an interaction between functionality group and block (younger children: $F(2,67)=6.91$, $p=0.002$, $p\eta^2=0.17$; older children: $F(2,98)=8.70$, $p<0.001$, $p\eta^2= 0.15$; adults: $F(2,85)=17.90$, $p<0.001$, $p\eta^2=0.30$), resulting from reduced smoothness for the F++ group in the GoGo block at all ages (younger children: $t(67)=3.31$, $p=0.02$; older children: $t(98)=5.22$, $p<0.001$; adults: $t(85)=5.20$, $p<0.001$). In addition, adults in the F- group demonstrated a small increase in smoothness in the GoGo block ($t(85)=3.24$, $p=0.02$). Overall, therefore, smoothness was preserved for mildly altered function but compromised by highly altered function.

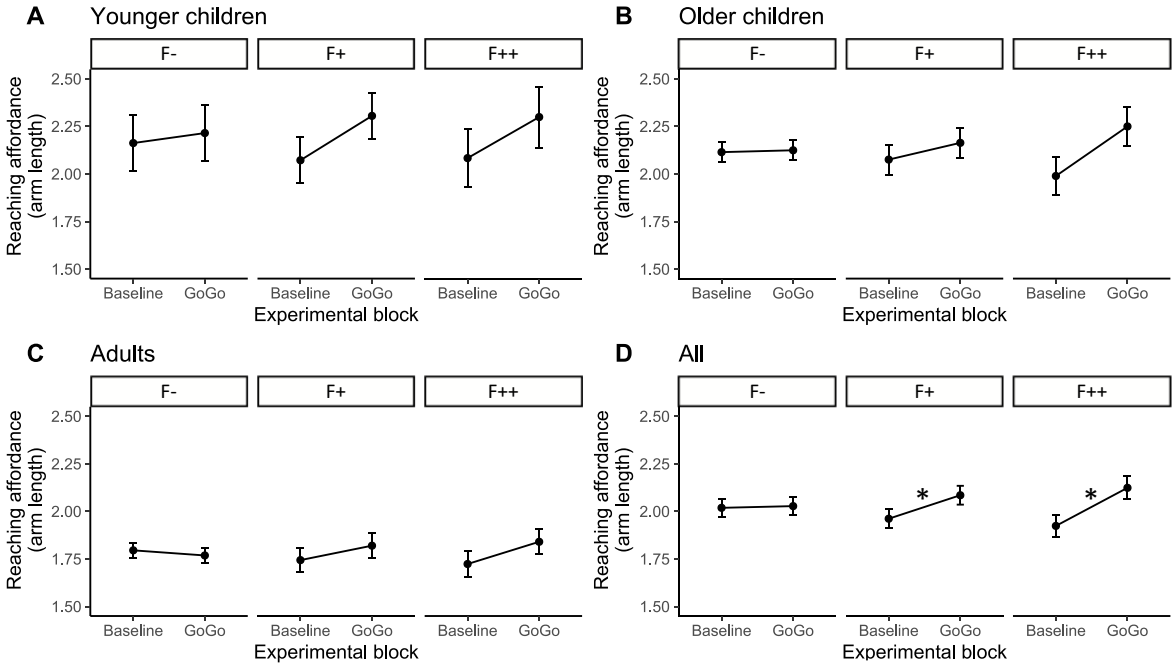
Figure 8. Arm extension smoothness as a function of age group, visual gain group and block. F-: reduced function; F+: increased function; F++: enhanced increased function: A) younger children, B) older children, C) adults, D) all three age groups. Error bars show the confidence interval. Significant interactions were followed up with post-hoc comparisons: asterisks indicate statistically significant single comparisons ($p<0.05$).



Reaching affordance

The distance at which a target was perceived as just reachable depended on age group and block. Overall, children perceived reaching affordance as longer (younger children: mean=2,19, SD 0.39; older children: mean=2.12, SD 0.39) than adults (mean=1.78, SD 0.39). It was also judged as longer after the GoGo block (baseline: mean=1.97, SD 0.44; GoGo: mean=2.09, SD 0.42). Finally, an interaction between functionality group and block (Table 1) showed that, independent of age, exposure to arms with increased function increased the reaching affordance (F+: $t(249)=3.50$, $p=0.007$; F++: $t(249)=5.27$, $p<0.001$; Fig. 9d).

Figure 9. Reaching affordance as function of age group, functionality group and block. F-: reduced function; F+: increased function; F++: strongly increased function: A) younger children, B) older children, C) adults, D) all three age groups. Error bars show the confidence interval. Asterisks indicate statistically significant single comparisons ($p<0.05$).

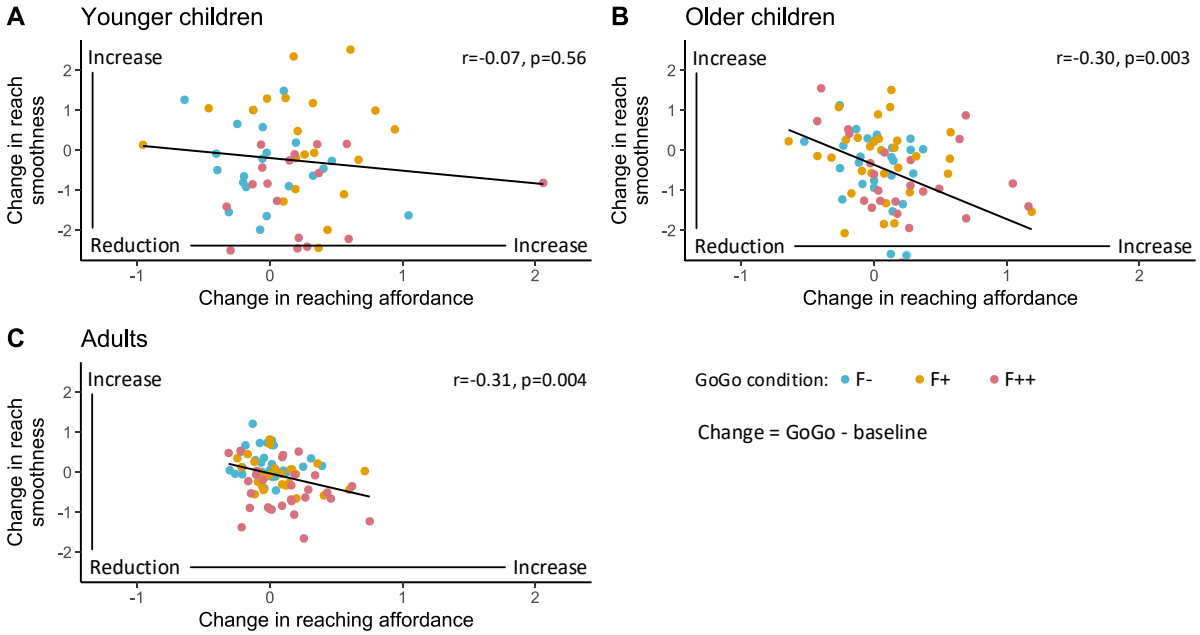


Sign. effects and interactions: Age Group, Block, Functionality*Block

Parameter correlations

For three variables (Reaching affordance, ownership, smoothness) we calculated the change values from baseline to GoGo blocks (GoGo - baseline). To examine how the body schema related to ownership and reach kinematics, we then calculated Spearman correlations between pairs of these variables: (i) reaching affordance and the sense of ownership and (ii) reaching affordance and smoothness (to index control efficiency). These two correlations were calculated for each of the nine age and functionality subgroups: none were significant. To increase power, we next collapsed across the functionality groups to calculate two correlations for each age group. For adults and older children, increased reaching affordance was associated with reduced smoothness from baseline to GoGo blocks (older children: r=-0.30, p=0.003; adults: r=-0.31, p=0.004; Fig. 10a-c).

Figure 10. Regression plots of parameter correlations (Spearman) between the changes in reach smoothness and reaching affordance from the baseline to the GoGo block: A) younger children, B) older children, C) adults. GoGo functionality groups are colour coded.



Discussion

Summary

In the present study, we tested the importance of body functionality to embodiment, by enhancing or reducing functionality using a virtual arm which reached further or less far than the participant's own. We expected that these functionality manipulations would lead to changes in several aspects of embodiment, including the sense of ownership, visuomotor control and reaching affordance. We also predicted that for children, the sense of limb ownership would be affected less by altered arm functionality, while adjustments in motor control would entail different sensorimotor solutions.

Embodiment & reaching affordance are constrained by function

Altered functionality affected the subjective embodiment of the virtual body. A sense of ownership was maintained for bodies with slightly modified function (F- or F+), suggesting plasticity in the range of body functions which users can embody. However, despite their potential advantages, bodies with extremely modified function (F++) reduced the sense of ownership and increased the experience of the virtual limbs as 'tool-like'. This reduction in ownership between 1.2 (F+) and 4 (F++) arm lengths is broadly in line with previous work, including a small-scale augmented reality "GoGo" experience (Feuchtner & Muller, 2017); and a study of a non-extendable long virtual arm (Kilteni et al., 2012). Lower ownership occurred predominantly but not exclusively in the adult F++ group. This implies that a constraining effect of function on ownership is somewhat more pronounced for adults than for children. The sense of agency was meanwhile reduced by subtle changes in either direction to the virtual arm's

function. Therefore, perhaps because of the motoric nature of the functional changes, agency seems more sensitive to function than ownership.

By using a body with clear functional modifications but minimal superficial alterations, the present study therefore provides a first direct test of how function affects subjective embodiment. We find that there is a range of altered body functions within which embodiment is maintained; that these ranges may be slightly narrower for adults than children; and that these ranges are wider for the sense of ownership than the sense of agency. These results motivate reconsideration of previous results in the light of functionality. Low ownership over wooden blocks in desktop bodily illusions (Tsakiris et al., 2010); or abstract hands in VR (F. Argelaguet et al., 2016) may be due to their non-functional nature; while acceptance of virtual tails (Steptoe et al., 2013), virtual third arms (A. S. Won et al., 2015), or extra fingers (Hoyet et al., 2016) may arise because their functionality is high. We suggest that functionality is a key constraining factor in embodiment, and that high functionality can enable embodiment even when superficial morphological characteristics differ significantly from the normal human body (Aymerich-Franch and Ganesh, (2016).

The Gogo experience did not just change the sense of embodiment, but also the body schema, as indexed by reaching affordance. We found that judged reachable distance increased following both the enhanced-functionality conditions (F+ and F++), but not the reduced functionality (F-) condition. This suggests that affordance adjustments may occur following both subtle and extreme *increases* in body functionality, while the status quo is maintained response to *decreased* functionality. The increased reaching affordance we observed with a longer virtual arm is in line with previous studies on long virtual arms (D'Angelo et al., 2018; Le Jeune et al., 2024; L. P. Y. Lin et al., 2020), or tools that functionally extend reaching distance (Cardinali et al., 2009; Ladavas & Serino, 2008). This shows that body schema adjustments occur both in contexts where the length of the virtual limbs is held constant (D'Angelo et al., 2018; Le Jeune et al., 2024) as well as in dynamic contexts like our present study. The unchanged reaching affordance we observed with a shorter virtual arm contrasts with Lin et al. (2020), who found reduced reachable distances with fixed-length 50% short arms. The discrepancy may be due to the smaller arm length reduction in our study, and/or the non-extendable arms used in theirs. Given our own finding that affordance changed in F+ but not F- conditions, we suggest that at least within this range of functions, there is asymmetric plasticity in the body schema, with greater tendency to embody increased-function than reduced-function limbs.

Motor competence remains high with altered-function arms

Motor performance remained impressively robust throughout the visual-proprioceptive discrepancy introduced in the GoGo blocks. Reaches were fast, well-calibrated to target distance, and relatively smooth, rather than being slow or erratic (Balasubramanian et al., 2012; Wong et al., 2021). The temporal synchrony between visual and proprioceptive information therefore seemed sufficient for participants to make the ‘unity assumption' (Chen & Spence, 2017; Welch & Warren, 1980) that both were caused by the same reaching movement. Performance was not perfect: the smoothness reduction observed for near targets suggests that overreaches and compensations occurred in the typical-function range (before the inflection point), with the motor control solution for the enhanced-function range of the reach

sometimes erroneously applied to the whole reach. Further, the association of smoothness with estimated subjective reaching affordance in older children and adults may indicate that uncertainty in sensorimotor control drove a subjective shift in the perceived action boundaries. Together, these findings have important implications for our understanding of how participants control functionally altered virtual bodies. Even without in-depth training, participants of all ages can show impressive degree of motor control over such bodies (Clode et al., 2024). However, they may overgeneralise control solutions within the altered range to the range of normal operation; further, the specifics of control may have after-effects on the user's perception of their functional abilities, though not for very young children.

Our participants calibrated peak velocity to target distance, which is a sign of well-controlled reaching (Flash et al., 2013; Viviani & Schneider, 1991; Yokoyama et al., 2018). Furthermore, once absolute arm length differences were accounted for, this calibration was found to be largely constant from baseline to GoGo conditions. This again indicates good control despite the altered 'GoGo' visual feedback. Indeed, since the targets were presented at 52%, 64%, 88%, and 100% arm extension in real physical space, and in each GoGo condition, *no motor adjustments were necessary* to successfully reach for the targets, and participants successfully retained the same solution across baseline, F- and F+ conditions. In contrast, in the F++ condition, participants of all ages were influenced by the amplified functionality of the virtual arm, executing their reaches with disproportionally faster velocities. Participants therefore found a consistent new motor solution for the functionally altered virtual arm. Examining the relation between *visual target distance* and peak velocity, however, revealed a degree of moderation in this adapted reaching. For the far targets (400% arm length in the F++ condition), participants held back: slopes were shallower than predicted by baseline distance-velocity calibration. Thus, adaptation to the visual virtual arm was simultaneously carefully offset by proprioception of the actual arm, through well-balanced movements that did not exceed the participant's actual physical boundaries. Our data therefore show that while experiencing new virtual body functions, participants of all ages (i) maintain baseline solutions where possible (ii) make motor adaptations in extremely altered conditions (iii) always choose safe movement solutions which balance the needs of the physical body well with those of the altered virtual body.

Interestingly, the faster reaches we observed in increased-function conditions distinguish our results from observed *reductions* in peak velocity following use of a long tool (Cardinali et al., 2009). In a study with a single target position, velocity reductions were interpreted as the tool inducing perception of a longer arm and relatively closer target position within peripersonal space (Cardinali et al., 2009). However, in examining calibration across a wider space, we observed that the longer GoGo arm in contrast caused increased velocity and reaching affordance at far distances. We suggest that this relationship between perceived arm length and peak velocity should be further investigated.

Specific motor solutions are age-dependent

In line with previous work (Ishak et al., 2014), there was remarkable consistency across age regarding changes in reaching affordance. Further, as we have seen the crucial calibration of peak velocity to distance was relatively constant across ages. In contrast, age affected several more nuanced aspects of reach kinematics, revealing that specific motor solutions did vary across ages. A first group of age differences were observed across blocks (regardless of functional alterations to the arm). Adults adopted higher peak velocities - perhaps with an

awareness that the animals could be fed by placing the hand within a relatively generous target volume, they chose speed over accuracy. However, they also left longer periods of deceleration after the early velocity peak. Therefore, adults arguably dealt with the speed-accuracy trade-off in more adeptly than children. In terms of how different *target distances* were treated, young children achieved peak velocity at a constant temporal proportion of the reach across all target distances, while adults adapted based on context, achieving peak velocity at a shorter proportional time for far distances (constant absolute time). A simpler motor schema in younger children again contrasts with adults' more refined, task-dependent solution (Schmidt, 2003; Shea & Wulf, 2005). For example, adults scaled up peak velocity more in response to *visual distance* than the children, which could indicate a better integration of visual information for planning a reach within the virtual environment. Overall, therefore, we argue that adults showed more nuanced movement patterns than children, adapting flexibly in demanding task conditions (Golenia et al., 2018); and relying strongly on visual information within the virtual environment. These observations add to the growing literature on reaching within VR for both adults (Clark & Riggs, 2020, 2021; Mangalam et al., 2024) and children (Alrashidi et al., 2024).

A second group of age differences were observed in relation to the GoGo function. Adults reduced the proportional time to peak velocity across target distances at baseline and maintained this solution in the Gogo block. In contrast, older children adopted adult-like scaling at baseline, but during GoGo reverted to a less developed mode of reaching, with long decelerative phases in the F++ condition and a child-like lack of scaling. Finally, younger children did not scale TPV at baseline, and during the increased-function GoGo blocks peaked sooner, allowing for a longer period of cautious deceleration. A similar pattern was seen in the spatial position of the velocity peak (though for adults this changed in the GoGo condition at near targets, perhaps due to overshoot). When confronted with modified functionality, therefore, adults appeared to almost effortlessly maintain control; older children demonstrated a fragile control that adapted less well than adults to new body functions; and younger children started with a simple solution and became cautious with the new virtual arm. Regarding age-related variation in GoGo movement solutions, we finally note that in the reduced-function GoGo condition, only adults managed to increase the smoothness of their reaching movements compared to baseline. While being consistent with smoother overall reaching movements in older participants (Kuhtz-Buschbeck et al., 1998; Schneiberg et al., 2002), adults also seem to take clever advantage of the apparently limiting F- condition. In sum, we find that in terms of reach control children are able to adapt relatively well to a newly functional virtual arm, while adults can maintain control to an impressive degree despite the visual-proprioceptive discrepancies in the GoGo conditions.

We suggest that an underlying limiting mechanism in children may reside in a poor ability to make fast online corrections of an ongoing movement without feedback (Gaveau et al., 2014; Mackrous & Proteau, 2016) by detecting any discrepancy between the predicted sensory outcomes of a movement (the forward model) and the actual limb position (Mackrous & Proteau, 2016; Wilson & Hyde, 2013). As a functional alternative to the predictive restriction, the impact of concurrent visual feedback may be greater during the GoGo experience. In our study, we observed this below the age of 8 years; while feed forward processes dominated in the older groups, who were *less* likely to adjust their absolute time to peak velocity in response to target distance or altered GoGo functionality. Thus, it seems that a greater reliance on feedback control during a reach, possibly due to the lack of fine-tuned feed forward control processes and accurate own body representations, increases the immediate adaptation to newly functional bodies. Further, we speculate that children's delayed time to peak velocity, in

absolute and in relative terms, might also indicate greater dependence on closed-loop, feedback control of reaching (Sainburg & Schaefer, 2004). This could indirectly demonstrate a stronger embodiment of the GoGo arms: a less mature early movement error detection process might have been less likely to flag the GoGo functional alteration as a deviation from (or in conflict with) expected normality and therefore left ownership unaffected.

Limitations and future directions

The most apparent methodological limitation of the current study is the non-anatomical rendering of the avatar's arms, which was not possible within the motion tracking solution. The adult sample, in particular, might have felt critical about the lack of elbow and shoulder joints. The Likert scale embodiment questions likewise represented a relatively coarse measure; more detailed interviews were not feasible in field settings with our large sample. A future follow-up study should provide an enhanced embodiment experience across a larger number of trials to determine whether children need longer exposure to the functionality manipulations to generate adult-like reaching solutions; and whether any effects that we observed might be transitory in nature, receding after habituation to the functionality alterations. It would be useful to probe how embodiment changes over a broader range of altered functions. Finally, virtual experiences without significant tactile input cannot be expected to elicit the same kind of embodiment as physical augmentation experiences (Clode et al., 2024; Kieliba et al., 2021).

Conclusion

Exposure to altered arm functionality in a VR game influenced subjective embodiment of the virtual arm, perceived reaching affordance, and motor control solutions in ways that were dependent on participants' age and the specific functional alteration experienced. The results show that participants of all ages were able to feel ownership over altered-function arms, suggesting some plasticity in the bodily self. Limits to this were, however, evident, particularly for adults: this constraining role of function may help account for previous work on embodiment of nonhuman objects. In embodying altered-function virtual bodies, participants altered their perceived reaching affordance, showing that these experiences can deeply affect the bodily schema. Likewise, although motor solutions were generally preserved across conditions, highly altered bodies elicited new motor solutions: these were in general more subtle and efficient for adults than for children. Therefore, while children were in general more liable to feel ownership with altered-function bodies, this was not coupled to better control. We suggest that these findings should inform our understanding of VR design. They also act as a powerful demonstration of the brain's inherent capacity for plasticity in representation of own-body function, which is present but also has observable limits.

Materials and methods

Participants

For this study, all participants were recruited and tested in the United Kingdom. We recruited 171 children of the age range from 5 to 10 years through a local primary school and public engagement events at the Life Science Centre, Newcastle upon Tyne, United Kingdom, and Durham University. This convenience sample was subdivided into a group of 70 children from

5.00 to 7.99 years (mean age=7.07 yrs, SD 0.78; 42 females) and a group of 101 children from 8.00 to 10.99 years (mean age= 9.24 yrs, SD 1.39; 44 females). In addition, a group of 88 young adults (mostly students from Durham University recruited for course credit) were included (mean age=22.53 yrs, SD 4.63; 63 females). Each participant was randomly assigned to one of three subgroups exposed to a specific visual control gain. Table S1 in the supplementary materials summarizes the demographic information for each of the 9 subgroups. The study was approved by the Durham University Psychology Department Ethics committee (reference number: PSYCH-2023-03-31T14_17_04) and performed in accordance with the standards of the 1964 Helsinki declaration of ethical principles for medical research involving human subjects and its later amendments. Written informed consent was provided by all participating adults and by all parents or legal guardians of child participants.

Materials and equipment

The virtual reality scene was custom-built in Unity and presented by means of a Meta Quest 2 headset. It was an outdoor scene (Fig. S1b): a meadow encircled by tall peaks, with trees and a flowing brook. A grassy mound was visible directly in front of the participant: target animals appeared from here, at a constant height which made leaning forward unnecessary. Further, participants were instructed not to lean forward or to stand during the virtual experiences. Finally, again to ensure a fixed position, child participants sat in a modified car seat with an oriented backrest and body height-adjusted headrest, mounted on a wooden platform. They were strapped in with a pair of diagonal seatbelts. Adult participants sat in a standard chair with armrests and were strapped in using a belt at chest height.

The participant's virtual avatar kept a seated posture on a stool. Participants could not see its trunk, lower body, or legs. The participant's virtual hands were rendered based on the headset's hand tracking and gesture recognition features. Two blue sleeves represented the arms, which connected the hands to the avatar's shoulders with simplified 'tubes'. The choice not to articulate the arms in an anatomically correct way (e.g. with wrist and elbow joints) allowed for a simple, portable motion capture solution.

Experimental design and protocol

Data collection was performed in a single session of ~20 minutes divided into two experimental blocks. The first block, which was identical for all participants, comprised practice trials and baseline data collection. The second block assessed participants during and after the experience of reaching with a functionally different 'GoGo' arm. In this block, one third of participants had a mild functional reduction (*F*-, 0.8 visual gain); one third had a mild functional enhancement (*F*+, 1.2 visual gain); one third had a strong functional enhancement (*F*++, 4.0 visual gain). In contrast to Poupyrev and colleagues (1996), we chose a linear relationship between real (Rr) and virtual (Rv) hand position (see equation, Fig. S1a). A linear relationship allowed the maintenance of a constant scaled gain of maximum arm length. An inflection point (D) at 2/3 arm length was chosen as a comfortable distance for a transition between normal and altered functionality. When the user extended the arm further than D (R*r* > D), the virtual arm length began to change in linear proportion with the real distance travelled.

Before the start of the reaching task, a participant's body height and forward extended arm length were measured manually, as well as electronically by the virtual reality headset. Any discrepancies between the manual and electronic measurements were used as a correction factor for the individual avatar representation of a participant. Within each block, participants were assessed in three domains of subjective experience and performance: unilateral goal-directed reaching, subjective perception of arm length, and subjective perception of embodiment. Each block started with a targeted reaching task, which comprised a gamified virtual reality experience, in which the participant fed animated animals (Fig. S1b). The animals were presented at four distances scaled to a participant's extended arm length at 52%, 64%, 88%, and 100% extension. The four target animal distances were chosen so that the closer two were not affected by the GoGo manipulation, while the more distant two were located beyond the inflection point D and therefore within the range affected by the altered GoGo functionality.

Participants performed eight practice trials (two reaches to each distance) and 12 test trials (3 to each distance) in the first block; followed by 12 trials (3 to each distance) in the experimental block. In the practice trials, the target collider volume in which the food had to be released for the animal was visible as a yellow cube in front of an animal. This target volume was invisible in the actual trials. In baseline and experimental trials, each target position occurred three times in a randomized order, personalized to each participant.

After each start of the reaching game, a participant had a 5 second exploratory period to scan the surrounding environment and to look at their virtual hands before the first reaching trial commenced. When a reaching trial started, the grassy mound was bare. A blue readiness cube hovered in front of the participant (Fig S1b) and a food item (apple or carrot) appeared after a hand was moved into this volume. Keeping the hand inside the cube and closing the fingers by contacting the tips of the thumb and the index and middle fingers caused the food item to jump into the participant's virtual hand. After pickup of the food item, an animal (randomised between a red panda, squirrel, or meerkat) appeared after a random delay (range 1s to 2s) at a specified target distance. Once the virtual hand was moved outside the readiness cube, the food item was attached to it and could not be released until the fingers were opened inside the animal's target volume. A reaching trial ended with successful release and transfer of the food item. At this point, the animal was shown to nibble the food item and then disappear, with a new trial starting 1 second later.

The second part of a block aimed to evaluate a participant's subjective reaching affordance – the perceived distance over which they could reach a target within a virtual environment. Instead of a grass mound, a long wooden table was presented in front of a participant: the tabletop was scaled in proportion to a participant's height measurement. At the far end of the table, a stack of books and a tankard were placed as familiar-sized objects to help guide size and distance perception in the virtual scene. The hands and arms of a participant's avatar were invisible, so the task was not influenced by current visual estimates of arm length. A red apple on a pedestal was presented at head level at variable locations on a participant's straight-ahead midline (Fig. S1c). The anterior-posterior position of the apple was determined by a vector of 50 distance positions ranging from 0.5 to 3 times a participant's arm lengths at logarithmically increasing spatial intervals. A participant's task was to evaluate after each object presentation whether they were able to reach the apple with their real arm (without leaning forward). The apple remained visible until a verbal yes/no decision was reported and logged by the experimenter. The next apple was presented at a different distance. The distance of the first presentation was randomly determined, drawn from all 50 possible distances. All subsequent

positions were determined by an adaptive staircase procedure (Parameter Estimation by Sequential Testing, PEST; Taylor & Creelman, 1967), which comprised 3 different step sizes depending on the trial number. In trials 1 to 7, after a 'yes' decision the next distance increased by 7 steps on the distance vector; after a 'no' decision it decreased by 7 steps. This step size was reduced to 3 following trials 8 to 12, and to 1 following trial 12. A maximum number of 30 trials was presented. Otherwise, the task was aborted when 5 yes/no reversals had occurred within the previous 7 trials, with counting towards this criterion starting after the 12th trial. Staircase adjustments could not fall below the closest or go above the furthest distance. Another exceptional termination criterion was 5 repetitions of the highest or lowest possible distance. The subjective reaching affordance based on perceived physical arm length was determined as the average of the final three presentations.

The third part of a block consisted of the administration of five questions about the subjective experience during the reaching task of the first part. The questionnaire was read aloud by the experimenter, with the virtual reality headset was removed so that a participant was also able to read it at the same time. The questionnaire (Table 2) had one item on each of five themes: 1. general user experience, 2. perceived limb ownership, 3. perceived level of agency in terms of limb movement control, 4. any perceived tool-like properties of the limbs, and 5. participant's suggestibility and answering bias. Each question was answered on a seven-point Likert scale (1: strongest disagreement, 4: neutral attitude, 7: strongest agreement).

Table 2. Embodiment questionnaire: questions and possible answers

Thematic category	Question	Disagreement	Neutral attitude	Agreement
General user experience	While I was feeding the animals, I thought …	○ … it was not so good (3) ○ … I didn't like it (2) ○ … I hated it (1)	○ … it was neither good nor bad (4)	○ … I loved it (7) ○ … I liked it (6) ○ … it was ok (5)
Limb ownership	While I was feeding the animals, the virtual hands and arms felt like they were my own hands and arms, or belonged to me…	○ … not really (3) ○ … not at all (2) ○ … absolutely not (1)	○ … in between (4)	○ … lots and lots (7) ○ … a lot (6) ○ … a little bit (5)
Limb agency	While I was feeding the animals, I felt that I was in control of moving the virtual hands and arms …	○ … not really (3) ○ … not at all (2) ○ … absolutely not (1)	○ … in between (4)	○ … lots and lots (7) ○ … a lot (6) ○ … a little bit (5)
Tool-like properties	While I was feeding the animals, the virtual hands and arms felt like a	○ … not really (3) ○ … not at all (2)	○ … in between (4)	○ … lots and lots (7) ○ … a lot (6) ○ … a little bit (5)

	litter picker or grabber tool rather than part of my body ...	○ ... absolutely not (1)		
Suggestibility and answering bias	While I was feeding the animals, my hair turned blue ...	○ ... not really (3) ○ ... not at all (2) ○ ... absolutely not (1)	○ ... in between (4)	○ ... lots and lots (7) ○ ... a lot (6) ○ ... a little bit (5)

Movement data post-processing and reduction

Data logging of hand and head movements was performed by the inbuilt headset tracking facility, with a sampling rate of 62 - 71 Hz. The movement data acquired during the virtual reality reaching task were processed in MATLAB 2019b (Mathworks, Natick, MA) in a sequence of steps. Movement data logs were converted from text format into MATLAB binary format and segmented into the individual reaching trials based on event logs separating a trial into four phases: preparation, readiness, reaching, post-release. For data analysis, only the readiness and reaching phases were considered.

All movement trajectories were inspected and data gaps in movement trajectories due to intermittent loss of motion tracking were interpolated using a spline interpolation algorithm. Intermittent data gaps in trajectories occurred in 20% of trial segments, predominantly at the starting position of a trial when a participant's hand was closest to the headset. Subsequently, all movement trajectories were smoothed using a dual-pass 4th order Butterworth low-pass filter with a cutoff frequency of 6 Hz.

For the determination of motor performance in each reaching trial, several spatial and temporal parameters were extracted based on the position and velocity time series along the forward reaching (AP, anteroposterior) axis (Fig. S1d). In a custom semi-automatic algorithm, the boundaries of a pre-reach baseline period and a post-reach steady state were specified manually. Onset of a reaching movement was determined as the first frame outside the baseline period, which exceeded at threshold of four times the standard deviation of AP velocity during the baseline period.

The moment a target animal appeared served as a time reference for any temporal parameters (a negative time-to-event means that the event happened before the onset of the target animal).The position and timepoint of maximum AP arm extension (i.e. reaching distance) before an end-of-reach steady state was achieved - as well as the position, point in time, and magnitude of AP peak velocity - were determined automatically. Time to peak velocity was expressed as a proportion of the duration of maximum reach; the position of peak velocity was expressed as a proportion of maximum reach amplitude. Finally, as a measure of the smoothness of reaching movements we calculated spectral arc length as per (Balasubramanian et al., 2015) across the combined readiness baseline and reaching phases. Figure 1e shows as a function of time the position, velocity, and arm extension for an illustrative reaching trial of a single participant. All extracted data files are available from the figshare database (10.6084/m9.figshare.28130111).

Statistical Analysis

All statistical computations were performed in RStudio 2023.06.1+524 using R version 4.3.1. Ordinal scaled data such as the questionnaire ratings were aligned-rank-transformed (Wobbrock et al., 2011) before statistical analysis. We then used mixed repeated-measures Analyses of Variance (ANOVA) with between-subject factors age group (three levels: 5-to-7-year-olds, 8-to-10-year-olds, adults) and GoGo functionality (three levels: F-, F+, F++) and within-subject factor experimental block (two levels: baseline, GoGo). The condition of target animal distance (four levels: 52%, 64%, 88%, 100% arm extension distance) was an additional within-subject factor for the movement-related performance parameters. Post-hoc single comparisons were performed following the Tukey procedure. Linear regressions were calculated and Spearman correlations between single parameters were performed using the parameters' difference values between the baseline to the GoGo block.

Author contributions

L.J., Y.P, M.G., X.P., D.C. designed and planned the study. L.J. has collected the data, L.J. and D.C. have designed the analysis, L.J. has processed the data, L.J. has analysed the data. L.J., Y.P, S.T., M.G., X.P., D.C. have prepared the manuscript.

Competing interest statement

The authors have no relevant financial or non-financial interests to disclose.

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Data availability statement

All extracted data files are available from the figshare database (10.6084/m9.figshare.28130111).

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