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# Fine Motor Control Underlies the Association Between Response Inhibition and Drawing Skill in Early Development

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Previous research shows that the development of response inhibition and drawing skill are linked. The current research investigated whether this association reflects a more fundamental link between response inhibition and motor control. In Experiment 1, 3- and 4-year-olds ($n$ = 100) were tested on measures of inhibition, fine motor control, and drawing skill. Data revealed an association between inhibition and fine motor control, which was responsible for most of the association observed with drawing skill. Experiment 2 ($n$ = 100) provided evidence that, unlike fine motor control, gross motor control and inhibition were not associated (after controlling for IQ). Alternative explanations for the link between inhibition and fine motor control are outlined, including a consideration of how these cognitive processes may interact during development.

Executive functions (EFs) are important to just about every aspect of life (Diamond, 2013): from school readiness as a child (Cameron et al., 2012) to marital harmony as an adult (Eakin, Minde, Hechtman, Ochs, & Krane, 2004). They are a group of top-down cognitive processes which include inhibitory control and working memory. These processes work together to facilitate thinking that is flexible and reflective.

The maturation of EFs continues into early adulthood. Nevertheless, developmental research has particularly focused on early childhood (Best & Miller, 2010; Garon, Bryson, & Smith, 2008), with response inhibition receiving most attention (Diamond, 2013). Response inhibition, the capacity to suppress impulsive behavior, is ineffective in most 3-year-olds, but usually improves substantially in little more than a year (e.g., Wiebe, Sheffield, & Espy, 2012; Willoughby, Wirth, & Blair, 2011). Evidence suggests that this rapid improvement in inhibition is, in turn, linked to several key changes in children's higher cognition. Beginning with a study by Carlson and Moses (2001), correlational evidence has suggested that improvement in inhibition is linked to the development of some important reasoning abilities (e.g., Apperly & Carroll, 2009; Beck, Carroll, Brunsdon, & Gryg, 2011; Benson, Sabbagh, Carlson, & Zelazo, 2013; Sabbagh, Moses, & Shiverick, 2006).

Recently it has been suggested that the emergence of picture drawing in early childhood is also linked to the development of response inhibition. Preliminary evidence (Riggs, Jolley, & Simpson, 2013) came from a study with 3- to 5-year-olds, comparing performance on a measure of inhibition to a measure of drawing skill. These findings were extended by Morra and Panesi (2017; Panesi & Morra, 2016), who found that drawing skill is associated with working memory as well as inhibition. The current study aimed to build on this research in two ways: first, to investigate whether the association between response inhibition and drawing skill is mediated by a more fundamental relation

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between inhibition and motor control; second, to investigate a specific instance in which response inhibition and drawing may be linked more directly.

Considering the first aim, Riggs et al. (2013) offered two accounts for why inhibition and drawing are associated. The "symbolic competence account" recognizes that the development of response inhibition has been linked to the development of symbolic understanding (e.g., Apperly & Carroll, 2009; Beck et al., 2011; Benson et al., 2013; Sabbagh et al., 2006). Symbolic representations encode a relation between a product of the mind (e.g., the category |dog|) and something in the world (a physical dog). Given that effective inhibition is associated with understanding these relations, it may also underpin the development of "representational" or figurative drawing. In a figurative drawing, the picture (a product of the mind) is visually similar to the subject it depicts in the world. Drawing a figurative picture requires an understanding of this relation (drawing–subject). If inhibition is associated with the development of symbolic understanding, then it may explain the observed association between improving inhibition and the emergence of figurative drawing (Riggs et al., 2013).

The "behavioral inhibition account" proposes a simpler role for response inhibition in drawing development. It may be that drawing develops through the inhibition of immature drawing behavior. For example, scribbling must be inhibited to produce the enclosed shapes which start the transition to figurative drawing (Riggs et al., 2013). The drawing of these shapes must in turn be inhibited, so that pictures which represent the subject's outline can be produced (Lange-Küttner, Kerzmann, & Heckausen, 2002). Finally, a drawer may have to inhibit drawing part of an object, when they see that object is partly occluded by another (Freeman & Cox, 1985). Thus, applying the behavioral inhibition account, response inhibition and drawing skill are associated because drawing skill advances through the direct suppression of immature drawing behavior.

Here we suggest another possibility, the "motor development account." The association of response inhibition and drawing skill may be mediated by the development of fine motor control. Fine motor control (e.g., controlling smaller muscles in order to grasp and manipulate objects—Wells, 2006) requires precise visuomotor coordination, principally through movement of the hands. Effective fine motor control is required for skilled drawing (e.g., Lange-Küttner, 2008; Toomela, 2002). There is also evidence linking inhibition and motor control more generally. These processes have been associated with the same brain areas (e.g., the prefrontal cortex and cerebellum) during development (e.g., Diamond, 2000; Koziol, Budding, & Chedekel, 2012). Difficulties in motor control and inhibition are often linked in neurodevelopmental disorders, particularly developmental coordination disorder (DCD). This developmental disorder is associated with difficulties in acquiring and executing motor control. There is extensive evidence, from data collected principally with 5- to 11-year-olds, that this disorder is linked with deficits in EFs (see Leonard & Hill, 2015 for a review).

Evidence for an association between response inhibition and motor control in young children is more limited. Two recent studies have investigated this relation in infancy (Gottwald, Achermann, Marciszko, Lindskog, & Gredeback, 2016; St. John et al., 2016). Gottwald et al. (2016), testing 18-month-olds, found a positive association between EFs and a measure of motor planning (Gottwald et al., 2016). Both inhibition and working memory were associated with prospective motor control (the ability to plan a reaching action ahead of time), but not with more general measures of motor control. In contrast, St. John et al. (2016) found a negative association between fine motor control and these EFs in 12-month-olds; however, the relation to work memory was positive at 24 months. Finally, there is some evidence for a relation between EFs and fine motor control in 5- to 6-year-olds (Livesey, Keen, Rouse, & White, 2006; Roebers et al., 2014). However, the relation between inhibition and motor control has not been investigated with 3- and 4-year-olds. As previously stated, this age group is of particular interest because inhibition improves most rapidly at this age, and this improvement is associated with important changes in children's reasoning and knowledge.

The second aim of the current research was to investigate the role of response inhibition in the developmental transition from intellectual realism to visual realism. These two drawing styles were extensively described by Luquet (1927/2001), and more recently summarized by Jolley (2010). In intellectual realism, children draw what they regard as the essential elements of a subject in their characteristic shape. They draw what they know is present, even if this means their drawings show multiple viewpoints. In contrast, visual realism is a later developing style, in which children draw only what they see from their own viewpoint. Piaget incorporated these drawing styles into his stage theory of cognitive development. His theory suggested that intellectual realism is cognitively "inferior" to visual realism, and that they are specific features of distinct developmental stages (Piaget & Inhelder, 1969).

This developmental transition has often been tested using objects such as a cup with the handle hidden from view by its body (Freeman & Janikoun, 1972), or two balls with one ball partly hidden behind the other (Cox, 1978). Consistent with Piaget's theory, younger children often drew the cup's handle and separated the two balls (intellectual realism), whereas older children drew only the elements that they could see (visual realism). Subsequent research showed that children's drawing is more fluid than Piaget suggested, with a range of factors influencing which style they adopted (e.g., Freeman & Cox, 1985). Nevertheless, this research suggests that the use of visual realism *does* increase during childhood (see Cox, 2005 for a review).

The possibility that adopting visual realism requires the "suppression" of intellectual realism had long been recognized, but not tested (e.g., Luquet, 1927/2001). More recently, it has been suggested that response inhibition in particular may facilitate this suppression (Ebersbach, Stiehler, & Asmus, 2011; Riggs et al., 2013). If effective inhibition is needed to suppress intellectual realism, then inhibition and intellectual realism should be *negatively* correlated. However, we recognized that this developmental shift to visual realism occurs around the age of 7–8 years (e.g., Freeman & Janikoun, 1972). In consequence, this is the age range in which inhibition is most likely to be used to suppress intellectual realism. In contrast, we tested 3- and 4-year-olds in the present study (the age at which inhibition develops most rapidly). In this younger age group, it was more uncertain what relation we would find between inhibition and intellectual realism.

## Experiment 1

In Experiment 1, 3- and 4-year-olds were tested on tasks measuring response inhibition, drawing, and fine motor control. Two age-appropriate response inhibition tasks were used: the day/night task and the grass/snow task (Petersen et al., 2016). These stimulus–response compatibility (S–RC) tasks have high inhibitory demands (e.g., Simpson et al., 2012). In the day/night task children must resist naming a picture, whereas in the grass/snow task they must resist pointing to a cued picture. The day/night task requires a verbal response, and the grass/snow task has only minimal motor demands (pointing is trivially easy for typically developing 3-year-olds). Thus, any correlation between inhibition and motor control, as measured by these tasks, is unlikely to depend on the inhibitory tasks' motor demands.

The four drawing tasks are also well-established measures of children's drawing skill. There were two free drawing tasks, which required children to draw a person (Cox & Parkin, 1986) and a house (Barrouillet, Fayol, & Chevrot, 1994). There were also two model drawing tasks, which required children to draw a cup with the handle occluded (Freeman & Janikoun, 1972), and two balls with one partially occluded behind the other (Cox, 1978). These four tasks were used to produce three measures of drawing skill. First, the pictures drawn in all four tasks were coded for whether or not they were figurative (i.e., the raters were able to recognize their subject matter). The *figurative representation scale* focused specifically on the transition from nonfigurative to figurative drawing. Second, the *figurative detail scale* was derived from established coding systems for the person task and house task and reflected the amount of figurative detail in these drawings. Third, the *intellectual realism scale* was derived from the cup task and balls task. An intellectually realistic drawing of the cup included the handle even though it was occluded, and an intellectually realistic drawing of the balls showed them as spatially separated objects (rather than overlapping).

Finally, fine motor control was measured using the Peabody Developmental Motor Scale (PDMS; Folio & Fewell, 2000). Eight tasks which contributed to the fine motor quotient of this scale were selected. These tasks involved construction, folding, and cutting, while tasks which required drawing were omitted. Pilot testing was used to identify tasks which returned a large amount of variance for children in the age range tested.

The symbolic competence and behavioral inhibition accounts both predicted a *direct* relation between inhibition and drawing skill, while the symbolic competence account specifically predicted an association between inhibition and the figurative representation scale. In contrast, the behavioral inhibition account predicted a correlation specifically between inhibition and the intellectual realism scale. Finally, the motor development account predicted that fine motor control would mediate the relation between inhibition and drawing skill.

## Method

### Participants

One hundred 3- and 4-year-olds participated in the experiment (*M* = 3 years 8 months, range = 3;0–4;6, *SD* = 6.77 months): 55 girls and 45 boys. The children attended preschools in the towns of Bury St Edmunds and Colchester in the east of England. The data were collected between January and March, 2016. All spoke English as their first language, and none had any behavioral or educational problems (based on teachers' report). The group was predominantly White and of mixed social class.

### Design

A within-participants design was used. The dependent variables were the three drawing measures: figurative representation, figurative detail, and intellectual realism. The independent variables were inhibitory capacity, motor capacity, age, and gender.

### Materials

The materials used in the drawing tasks were plain A4 paper, pencils, a mug (height = 12 cm, diameter = 6 cm), and two balls (diameter = 9 cm). The grass/snow tasks materials consisted of two pictures: one of the moon in a night sky and the other of the sun in a day sky (height = 12 cm, width = 12 cm). The day/night task also used a flip book which contained 20 of these pictures. Finally, the motor tasks used materials from the fine motor quotient of the PDMS, 2nd ed. (PDMS–II; Folio & Fewell, 2000).

### Procedure

A total of 14 tasks were administered in two sessions, each lasting about 20 min (Table 1). There were four drawing tasks, two inhibition tasks, and eight fine motor control tasks. Children were tested individually in a room adjacent to their main classroom or in a quiet corner off the classroom itself. Each child was seated across the table from the first experimenter (E1) and was told that they were going to play some fun games. The second experimenter (E2) sat next to the child and recorded their responses.

*Drawing task.* For each drawing task, a piece of plain A4 paper and a pencil were placed on the table in front of the child. In the first session, for the person task, E1 asked children, "Can you draw a picture of yourself?" In the cup task, the cup was placed on the table in front of the child in such a way that the handle was not visible. Children were then asked, "Can you draw a picture of this cup?" If they asked any questions about how to draw it, they were told to ". . . just do your best drawing." In the second session, for the house task, children were asked, "Can you draw a picture of your house?" (or *a* house, if they said they did not live in one). In the final drawing task, the balls task, two balls were placed on the table in front of the child so that one ball was half-occluded by the other. Children were asked, "Can you draw a picture of these balls?"

The drawings were scored on three scales. Each picture was coded as either figurative or nonfigurative (figurative representation scale, scored 0–4). The person and house tasks were also coded as follows. The person task was scored according to the

Table 1
*Fixed Order of Tasks Used in Experiments*

| Experiment 1 | | Experiment 2 | |
|---|---|---|---|
| Session 1 | Session 2 | Session 1 | Session 2 |
| 1. Person | 8. House | 1. Stand on one foot | 10. Button strip |
| 2. Grass/snow | 9. Day/night | 2. Jump up | 11. Dropping pellets |
| 3. Cup | 10. Balls | 3. Catch a ball | 12. Grass/snow task |
| 4. Lace a string | 11. Cut a circle | 4. Grasp a marker | 13. Imitate |
| 5. Cut a square | 12. Fold paper | 5. Day/night task | 14. Walk backwards |
| 6. Build a pyramid | 13. Diagonal pyramid | 6. Lace a string | 15. Bouncing ball |
| 7. Button strip | 14. Touch fingers | 7. Stand on tiptoe | 16. Tapping task |
| | | 8. Jump forward | 17. Touch Fingers |
| | | 9. Hit a target overhand | 18. Build a steps |
| | | | 19. British Picture Vocabulary Scale |

Cox and Parkin (1986) scale. This is a 5-point scale: 1 (*scribble*), 2 (*distinct forms*), 3 (*tadpoles*), 4 (*transitional figures*), or 5 (*conventional figures*). The house task was scored using a revised version of Barrouillet et al.'s (1994) scale. Twelve items scored: "outline of house," "roof," "roof shape," "door," "door handle," "base of the house," "two or more windows," "position of windows," "proportion of windows," "curtains," "extraneous items," and "perspective." The score for the person and house drawings was summed to produce the figurative detail scale (scored 0–17). The cup and balls tasks were scored on the intellectual realism scale (scored −2 to 2). The cup drawing scored 1 if the handle was included (intellectual realism), and −1 if it was omitted (visual realism). The balls drawing was scored 1 if the balls were drawn separately (intellectual realism), and −1 if they overlapped (visual realism).

*Inhibition tasks.* The day/night and grass/snow procedures were taken from Simpson and Riggs (2009). In the grass/snow task, E1 explained that they were going to play a "silly game" in which the child would have to point to two pictures. Children were shown the sun and moon pictures and asked to name them. E1 then explained that in the game they should point to the sun picture when she said "moon," and to the moon picture when she said "sun." The child was explicitly told not to point to the named pictures. E1 then "talked children through the rules" by saying the two names and getting them to point to the appropriate picture (e.g., ". . . so when I say sun can you show me which picture you have to point to—confirming that they were correct or correcting them if necessary by referring to the rules"). Children then received four practice trials (order: sun, moon, sun, moon) with feedback. If, for example, the child pointed to the moon when the experimenter said "sun," the experimenter confirmed that this was the correct response. If, however, the child pointed to the sun, the experimenter said that this was wrong because moon was correct. Children next received 16 test trials in the same pseudorandom order (ABBABAABBABAABAB) and with no feedback. E2 coded children's responses. An identical procedure was used with the day/night task (except that children produced verbal responses). The four practice and 16 test trials were presented using a flip book which contained 20 pictures. The two scores were summed to produce a measure of inhibitory capacity (scored 0–32).

*Fine motor control task.* Of the eight motor tasks, seven were taken from the fine motor quotient from the PDMS–II: button strip (task number 24), finger touching (26), fold paper (50), lacing a string (58), cut a circle (65), cutting a square (68), pyramid building (task 69). Details of how to administer these tasks can be found in the PDMS–II manual. The eighth task, the diagonal pyramid building task, was a modification of the pyramid building task with increased difficulty. The pyramid was constructed with edges adjacent (rather than faces as in the original task). There was also a distance of a few millimeters between each block (rather than the faces being in contact). Pilot data suggested that this was the most demanding task—although some children could complete or partially complete it. All tasks were scored 0, 1, or 2 for no, partial, or completed performance following criteria set out in the PDMS–II manual. Fine motor capacity was therefore scored between 0 and 16.

## *Results*

Table 2 summarizes descriptive statistics for age and gender, as well as the five performance variables (inhibitory capacity, fine motor capacity, figurative representation, figurative detail, and intellectual realism). Table 3 shows the correlations between these variables. Figurative detail was the only variable correlated to gender, with girls

Table 2
*Descriptive Statistics*

| Variables | *n* | Minimum | Maximum | *M* | *SD* |
|---|---|---|---|---|---|
| Experiment 1 | | | | | |
| Inhibitory capacity | 100 | 0 | 32 | 18.3 | 11.4 |
| Fine motor capacity | 100 | 0 | 16 | 9.14 | 4.77 |
| Figurative representation | 100 | 0 | 4 | 1.91 | 1.46 |
| Figurative detail | 100 | 0 | 15 | 4.67 | 4.52 |
| Intellectual realism | 65[a] | −2 | 2 | 0.58 | 1.31 |
| Age | 100 | 36 | 54 | 44.2 | 6.77 |
| Experiment 2 | | | | | |
| Inhibitory capacity | 100 | 0 | 48 | 25.2 | 16.4 |
| Fine motor capacity | 100 | 0 | 12 | 6.78 | 3.25 |
| Gross motor capacity | 100 | 0 | 17 | 7.04 | 3.74 |
| Age | 100 | 36 | 59 | 48.4 | 7.81 |
| General intelligence | 98 | 0 | 56 | 26.9 | 15.1 |

[a]Number of children who produced at least one figurative picture in the visual realism drawing tasks.

Table 3
*Correlations*

| Variables | Inhibitory capacity | Fine motor capacity | Figurative representation | Figurative detail | Intellectual realism |
|---|---|---|---|---|---|
| Experiment 1 | | | | | |
| Gender | −.003 | .031 | .151 | .238* | .047 |
| Age | .470** | .577*** | .597*** | .544*** | .540*** |
| Inhibitory capacity | — | .635*** | .565*** | .456*** | .574*** |
| Fine motor capacity | | — | .735*** | .683*** | .530*** |
| Figurative representation | | | — | .844*** | .567*** |
| Figurative detail | | | | — | .466*** |

| Variables | Inhibitory capacity | Fine motor capacity | Gross motor capacity | General intelligence |
|---|---|---|---|---|
| Experiment 2 | | | | |
| Gender | −.112 | −.063 | −.059 | −.017 |
| Age | .700*** | .659*** | .675*** | .590*** |
| Inhibitory capacity | — | .749*** | .631*** | .563*** |
| Fine motor capacity | | — | .750*** | .647*** |
| Gross motor capacity | | | — | .600*** |

*$p < .05$. **$p < .01$. ***$p < .001$.

outperforming boys a little (girls 5.64, boys 3.49). All the other variables were positively correlated.

Three univariate regression analyses were conducted using age, gender, inhibitory capacity, and fine motor capacity as predictors with figurative representation, figurative detail, and visual realism as output variables (Table 4). Fine motor capacity, age, and gender (but not inhibitory capacity) were significant predictors of both figurative representation and figurative detail. In contrast, only inhibitory capacity and age were significant predictors of intellectual realism. The data were subjected to mediated regression analyses controlling for age and gender (Figure 1). We did so by running a bias-corrected and accelerated bootstrap analysis using the INDIRECT macro developed by Preacher and Hayes (2008). This analysis revealed that fine motor capacity mediated the effect of inhibitory capacity on figurative representation, 95% CI [.0146, .0501], and figurative detail, 95% CI [.0471, .1747], but not intellectual realism, 95% CI [−.0033, .0203] (Figure 1). Only the direct relation between inhibitory capacity and intellectual realism remained significant after mediation was removed.

### *Discussion*

Experiment 1 provided evidence that response inhibition, fine motor control, and drawing skill are linked in early childhood. Mediated regression analysis (after controlling for gender and age) showed that inhibitory capacity and fine motor capacity were associated, and that this association predicted performance on the figurative representation and figurative detail scales. The observation of this mediated relation provides the first support for our motor development account. This account proposes that children's response inhibition and drawing skill are linked because both are associated with fine motor control. Moreover, the absence of a direct relation between inhibitory capacity and performance on the figurative representation scale (i.e., the transition from nonfigurative to figurative drawing) provides no support for the symbolic competence account. This account proposes that effective inhibition is associated with the development of symbolic understanding, which in turn promotes the onset of figurative drawing (Riggs et al., 2013). Likewise, there was no direct relation between inhibitory capacity and figurative detail (the amount of figurative detail in the person and house drawings). Thus, the data failed to support the behavioral inhibition account (Riggs et al., 2013), which proposes that drawing skill advances through the suppression of previously established drawing behavior.

Nevertheless, there was some support for the behavioral inhibition account: there was a direct relation between inhibitory capacity and performance on the intellectual realism scale (the extent

Table 4
*Regression Analyses*

| | Output variable | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Figurative representation | | | Figurative detail | | | Intellectual realism | | |
| | $F(4, 95) = 37.3, R^2 = .611$ | | | $F(4, 95) = 28.7, R^2 = .547$ | | | $F(4, 60) = 11.9, R^2 = .442$ | | |
| Predictor | β | *t* | *p* | β | *t* | *p* | β | *t* | *p* |
| Experiment 1 | | | | | | | | | |
| Age | .239 | 3.01 | .003 | .222 | 2.59 | .011 | .269 | 2.12 | .038 |
| Gender | .188 | 2.03 | .045 | .216 | 3.12 | .002 | .018 | 0.18 | .855 |
| IC | .128 | 1.53 | .130 | .006 | 0.064 | .949 | .364 | 3.11 | .003 |
| FMC | .511 | 5.63 | < .001 | .545 | 5.56 | < .001 | .164 | 1.23 | .225 |

| | Output variable | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Inhibitory capacity | | | Fine motor capacity | | | Gross motor capacity | | |
| | $F(5, 92) = 31.2, R^2 = .629$ | | | $F(5, 92) = 44.3, R^2 = .707$ | | | $F(5, 92) = 31.9, R^2 = .635$ | | |
| Predictor | β | *t* | *p* | β | *t* | *p* | β | *t* | *p* |
| Experiment 2 | | | | | | | | | |
| Age | .351 | 3.80 | < .001 | .013 | 0.151 | .526 | .278 | 2.95 | .004 |
| Gender | .044 | 0.698 | .487 | .018 | 0.320 | .750 | .013 | 0.200 | .842 |
| GI | .042 | 0.472 | .638 | .193 | 2.55 | .013 | .110 | 1.270 | .207 |
| IC | — | — | — | .373 | 4.43 | < .001 | .014 | 0.137 | .891 |
| FMC | .471 | 4.43 | < .001 | — | — | — | .492 | 4.71 | < .001 |
| GMC | .014 | 0.137 | .891 | .395 | 4.71 | < .001 | — | — | — |

*Note.* All models are significant at $p < .001$. IC = inhibitory capacity; FMC = fine motor capacity; GMC = gross motor capacity.

to which children draw what they see, rather than what they know). As we noted in the Introduction, it has previously been suggested this correlation might be negative—with effective inhibition leading to the suppression of intellectual realism (Ebersbach et al., 2011; Riggs et al., 2013). However, this may only occur later in childhood, as children come to value visual realism. Our data suggest younger children may use their inhibition in a different way: to promote intellectual realism rather than suppress it (we return to a consideration of why this might be in the General Discussion).

## Experiment 2

Experiment 1 investigated fine motor control because this kind of motor ability is essential for drawing (Lange-Küttner, 2008; Toomela, 2002). The data suggested that response inhibition and fine motor control are associated in early childhood. In Experiment 2, we investigated this relation further. First, we wished to determine whether this association extends to gross motor control (i.e., the control of large muscle groups to position the whole body, maintaining a stable posture, and responding to external change—Wells, 2006). The PDMS was again used. Nine tasks which contribute to the gross motor quotient of this scale were tested: three each from the stationary (sustaining stationary control of the whole body), locomotion (moving the whole body), and object manipulation (catching and throwing) subtests. Six tasks were taken from the fine motor quotient: three each from the grasping and visual–motor subtests. As in Experiment 1, pilot data were used to identify "high-variance" tasks.

Second, we wished to confirm that the association between inhibition and motor control could not be explained by general intelligence. The British Picture Vocabulary Scale, 2nd ed. (BPVS–II), a test of receptive vocabulary, was used as it is highly correlated with general intelligence (Dunn & Dunn, 2009; Glenn & Cunningham, 2005). In Experiment 2, three S–RC tasks were used to assess response inhibition: day/night and grass/snow tasks, as stated earlier, plus the tapping task which requires the suppression of imitation (Diamond & Taylor, 1996).

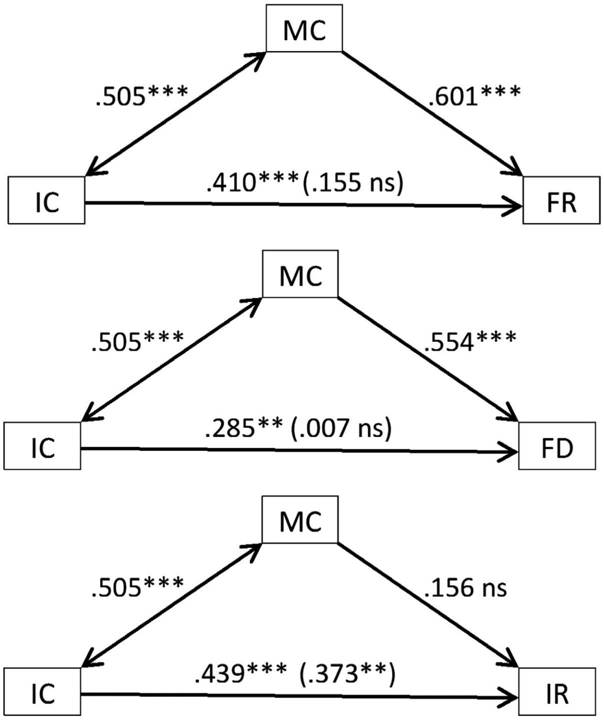

*Figure 1.* Mediated regression analysis for Experiment 1 of figurative representation (FR), figurative detail (FD), and intellectual realism (IR). Inhibitory capacity (IC) is shown as the predictor and motor capacity (MC) the mediator, with age and gender entered as covariates. The arrows between IC and MC are shown as bidirectional, as we do not know what causes this association. Partial correlations (controlling for age and gender) and their significance are shown (*ns*, not significant, $**p < .01$, $***p < .001$). The values in brackets additionally control for MC.

## *Method*

### *Participants*

One hundred children between the ages of 3 and 4 years participated in the study ($M = 3;11$, range = 3;0–4;11, $SD = 7.81$ months): 45 girls and 55 boys. The children were recruited from preschools and nurseries in the town of Colchester in England. The data were collected between September and December, 2016. None of the children had any reported behavioral or learning difficulties. They all spoke English fluently and were predominantly White, although the sample of children was of a mixed social background.

### *Design*

A within-participants design was used. The dependent variable was inhibitory capacity. The independent variables were fine motor quotient, gross motor quotient, general intelligence, age, and gender.

### *Procedure*

Testing was conducted as stated earlier with two experimenters in two sessions, (each lasting between 20 and 30 min). Nineteen tasks were administered with the first session consisting of an S–RC task and eight PDMS–II tasks; the second session comprised two S–RC tasks, seven PDMS–II tasks, and the BPVS–II. All 19 tasks were presented in a fixed order (Table 1).

The BPVS–II was administered according to the standard procedure for this measure of receptive vocabulary in British English (Dunn & Dunn, 2009). The procedure for the day/night and grass/snow tasks was identical to that used in Experiment 1. For the tapping task, the experimenter and child each had a wooden dowel. The experimenter explained that in the game when she tapped once with the dowel the child should tap twice, and when she tapped twice the child should tap once.

Nine tasks were taken from the gross motor quotient of PDMS–II: three from each of the subtests. Standing on tiptoes (task number 22), standing on one foot (23), and imitating movements (26) from the stationary subtest; jumping up (72), jumping forward on one foot (73), and walking a line backward (78) from the locomotion subtest; catching a ball (17), hitting a target overhand (18), and bouncing ball (21) from the object manipulation subtest. New tasks were sought for the grasping and visual–motor subtests. Pilot testing revealed that only three other tasks from the PDMS–II produced substantial variance in this age range, and so were included in our battery: grasping a marker (22), dropping pellets (74), and building steps (75). The remaining three tasks were taken from Experiment 1 (lacing a string, button strip, finger touching). Details of how to administer and score these tasks can be found in the PDMS–II manual.

## *Results and Discussion*

Table 2 summarizes descriptive statistics for age and gender, as well as the four performance variables (inhibitory capacity, fine motor capacity, gross motor capacity, and general intelligence). Table 3 shows the correlations between these six variables. All the variables were positively correlated with each other except for gender. Three univariate regression analyses were conducted using age, gender, general intelligence, inhibitory capacity, fine motor capacity, and gross motor capacity (Table 4). Fine motor capacity and age explained a substantial amount of variance in inhibitory capacity. With fine motor capacity as the output variable, inhibitory capacity, gross motor capacity, and general intelligence were all significant predictors. Finally, for gross motor capacity, fine motor capacity and age were significant.

Experiment 2 replicated the finding from Experiment 1 that preschoolers' response inhibition and fine motor control were substantially associated (after partialing-out gender and age and, in Experiment 2, general intelligence). Interestingly, this relation did not extend to gross motor control. While gross and fine motor control were associated, gross motor control and response inhibition were not.

## General Discussion

Our data support the previous finding that preschool children's response inhibition and drawing skill are associated (Morra & Panesi, 2017; Panesi & Morra, 2016; Riggs et al., 2013). In addition, they advance our understanding of the role of response inhibition in early development. The most important finding was the strength of the association between inhibition and fine motor control (while inhibition and gross motor control were not linked). We also found that this association accounted for the relation observed between inhibition and two of our measures of drawing skill (figurative representation and figurative detail scales). The pattern of results was different for our final measure of drawing skill: intellectual realism. The adoption of intellectual realism (drawing what you know is there), rather than visual realism (drawing what you see), was *not* associated with fine motor control, but was associated with inhibition.

### *The Relation Between Response Inhibition and Drawing Skill*

First, we focus on preschoolers' figurative drawing skill. In the Introduction, we set out three accounts of the relation between response inhibition and this skill. The symbolic competence account proposes that effective inhibition is associated with the domain-general development of symbolic understanding, and that this leads to the transition from nonfigurative to figurative drawing (Riggs et al., 2013). The behavioral inhibition account proposes that inhibition is needed to suppress immature drawing behavior (e.g., Riggs et al., 2013). Finally, the motor development account proposes that inhibition improves drawing skill through its association with fine motor control.

Our data provide clear support for the motor development account. There was a substantial mediated relation between response inhibition, fine motor control, and figurative drawing (Figure 1). Figurative drawing makes large demands on the sensorimotor system. It may be that effective fine motor control frees a child's cognitive resources to dedicate to the higher order aspects of drawing, such as figurative detail. There was no significant direct relation between inhibition and two of our drawing measures (figurative representation and figurative detail scales). Thus, these data failed to support the symbolic competence and behavioral inhibition accounts.

There was, however, some data consistent with the behavioral inhibition account. Inhibitory capacity was directly associated with performance on the intellectual realism scale. Preschoolers with effective inhibition seem to use it to *promote* intellectual realism. In contrast, several authors have previously suggested that children are motivated to draw visually realistic pictures, and that better inhibition promotes this, by enabling them to inhibit behavior which leads to an intellectually realistic drawing (Ebersbach et al., 2011; Riggs et al., 2013). Thus, we observed the *opposite* relation to that which has been previously proposed.

Our data, however, are not as contrary to established theory as they might at first seem. As noted in the Introduction, the most common age group selected to investigate the developmental shift from intellectual to visual realism is middle childhood (around 7–8 years—e.g., Freeman & Janikoun, 1972), whereas we tested 3- and 4-year-olds. It is possible that older children, as established theory suggests, do indeed have an increasing preference for visual realism. Nevertheless, *younger* children may have a different preference (see Brooks, Glenn, & Crozier, 1988). Perhaps the 3- to 4-year-olds, who participated in our study, were actually motivated to draw using intellectual realism but needed effective response inhibition to achieve this.

One interpretation of the positive correlation between response inhibition and intellectual realism, supporting the behavioral inhibition account, is that preschool children must inhibit visual realism in order to engage in intellectual realism. Perhaps for preschool children, the "unreflective default" is to simply draw what you see. If this is the case, then young children would need effective inhibition to produce a drawing which goes beyond a superficial depiction of visual realism, and display their deeper understanding of the scene in front of them. As far as we are aware, only studies of precocious young artists and autistic savants gifted in drawing have found evidence of visual realism in early drawing development (e.g., Golomb, 1992). A more modest interpretation of the correlation between inhibition and intellectual realism is to suggest that inhibition promotes the production of the pictorial features which characterize intellectual realism (e.g., drawing a cup's handle), rather than being used to actively suppress visual realism.

### *The Relation Between Response Inhibition and Motor Control*

Previous research has found robust evidence for a relation between motor control and several EFs in older children and adolescents diagnosed with DCD (see Leonard & Hill, 2015 for a review). There is also some evidence for such a relation between inhibition and motor control in typically developing infants (Gottwald et al., 2016; St. John et al., 2016), 5- and 6-year-olds (Livesey et al., 2006; Roebers et al., 2014), and adolescents (Rigoli, Piek, Kane, & Oosterlaan, 2012). The current study provides the first evidence for an association between response inhibition and fine motor control in 3- and 4-year-olds: the time when inhibition is developing most rapidly (e.g., Wiebe et al., 2012; Willoughby et al., 2011). The evidence presented here is correlational; we consider two ways to explain this association: first, that effective inhibition leads to effective fine motor control, and second, that embodied cognition explains why fine motor control and inhibition develop together.

Why might response inhibition improve fine motor control? An obvious place to start is with existing theories that address the direct relation between inhibition and drawing (Riggs et al., 2013). However, neither of the accounts outlined in the Introduction seem to apply to fine motor control. The symbolic competence account suggests inhibition aids the development of symbolic understanding (e.g., Sabbagh et al., 2006). However, actions requiring fine motor control, like doing-up a button, require no symbolic understanding. The behavior inhibition account proposes that drawing skill advances through the inhibition of previously established drawing behavior (Ebersbach et al., 2011; Riggs et al., 2013). Most actions requiring fine motor control do not seem to depend on the inhibition of previously established behaviors.

A different approach to explaining the relation between inhibition and motor control is to consider how preschooler's response inhibition develops. One possibility, compatible with the behavioral inhibition account, is that the *strength* of inhibition increases, enabling *inappropriate* responses to be stopped (Simpson & Riggs, 2007). An alternative is that inhibition improves because behavior is *slowed*, and more care taken to produce the *appropriate* response (Diamond, Kirkham, & Amso, 2002). Indeed, there is evidence that preschoolers perform inhibitory tasks better when their responding is slowed (e.g., Simpson et al., 2012; although see Barker & Munakata, 2015, and the response of Ling, Wong, & Diamond, 2016).

The proposal that effective response inhibition is the product of slowed responding could explain the link between response inhibition and certain kinds of motor control. For example, when toddlers respond more slowly, they perform better on a precise motor control task (building a tower from blocks), while performance on an imprecise motor task (placing blocks in a container) is unaffected (Chen, Keen, Rosander, & von Hofsten, 2010). Similarly, we found that inhibition is associated with fine motor control (doing-up a button), which might benefit from slowed responding, but not with gross motor control (catching a ball), which might not. In the case of drawing, Lange-Küttner (2000) has also argued that the emergence of sophisticated drawing techniques (e.g., connecting distinct elements of the represented subject) depends on modifying *fast* procedural routines. Consistent with this proposal, she found evidence that young children do slow their drawing speed, when producing open rather than closed shapes (Lange-Küttner, 1998). All of these findings are compatible with the proposal that effective response inhibition improves motor performance by slowing responding.

Moving on to the suggestion that fine motor control improves response inhibition, the S–RC tasks used in the current study were chosen specifically because they have minimal motor demands. The day/night task required a verbal response. The grass/snow and tapping task did require a manual response, however, these responses were undemanding (e.g., pointing to any part of the picture) and made without time pressure. Thus, it seems very unlikely that effective fine motor control improved performance on our inhibitory tasks because of their inherent motor demands. In contrast, the theory of embodied cognition offers an explanation for how the development of motor control and EFs are linked.

The embodied cognition approach suggests that human cognition is constructed through the physical interaction of our bodies with the world (see Marshall, 2016; Shapiro, 2011 for reviews). Building on the earlier work of Piaget (1952), in which the sensorimotor stage is the first step in cognitive development, current theory goes on to suggest that subsequent cognitive development depends on an individual's ability to act upon the world through the control of their bodies (Wilson, 2002). An example is the A not B task. The goal of an infant in this task is to find an object hidden at a new location, after previously retrieving it from another location. In order to reach to the new location, inhibition and working memory work together with the motor system (e.g., Thelen, Schoner, Scheier, & Smith, 2001). Such bidirectional interactions between the executive and motor domains are highlighted in Dynamic Systems Theory (e.g., Smith & Thelen, 2003), and reflected in the interaction of the brain regions associated with them (e.g., Diamond, 2000; Koziol et al., 2012).

It is unclear, however, whether specific aspects of the motor system are more closely linked with EFs than others, and how these linkages change during development. The current data suggest that fine motor control, but not gross motor control, is associated with response inhibition in early childhood. Previous research with younger children reported that gross motor control is related to response inhibition at 24 months, but not at 12 months (St. John et al., 2016). Taking a dynamic systems approach, it could be suggested that different aspects of the motor system interact with EFs at different ages. For example, the transition from crawling to walking (in the 2nd year) may increase the integration of gross motor control with EFs. Later still, fine motor control dominates, as preschoolers develop skills such as drawing and dressing. Future research would benefit from a longitudinal approach, to better understand these interactions, and thus provide a fuller explanation of the link we have found between fine motor control and inhibition in preschool children.

### *Conclusion*

This is the first study to demonstrate an association between response inhibition and fine motor control in 3- and 4-year-olds. Our data suggest that this association explains much, if not all, of the relation between inhibition and the emergence of early drawing skill: emphasizing the importance of this association in children's everyday behavior. Future work, both empirical and theoretical, needs to bring together data suggesting that executive and motor domains are linked in infancy (Gottwald et al., 2016; St. John et al., 2016), childhood (Livesey et al., 2006; Roebers et al., 2014; as well as our data presented here), and adolescence (Rigoli et al., 2012). In this way, a coherent theory can be constructed which binds together these findings, made with children of different ages using different tasks, and explains how specific EFs are linked with specific aspects of motor control across development. It is a considerable challenge, but one whose solution will represent a substantial advance in our understanding of cognitive development.

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