**The associations between spatial skills and specific components of physics knowledge: a
primary school classroom study on sound propagation**

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Abstract

Previous research demonstrates an association between spatial ability and science achievement in primary school aged children. However, little is known about the mechanisms driving this relationship. We therefore investigated the associations between children's spatial skills and components of physics learning (knowledge retrieval vs. conceptual knowledge [predictions and explanations]). Participants ($N = 107$; mean age: 9.2 years) completed a set of spatial tasks based on the '2 x 2' (intrinsic-extrinsic; static-dynamic) model. They also participated in a whole-class science lesson about sound, followed by an assessment of science knowledge. After controlling for vocabulary and prior knowledge, spatial ability was not associated with knowledge retrieval scores. Mental rotation was most closely associated with conceptual predictions ($r^2 = 4\text{-}7\%$). However, mental folding was most strongly associated with conceptual explanations ($r^2 = 9\text{-}14\%$). These findings suggest that future spatial intervention studies designed to enhance children's science learning should target these intrinsic-dynamic spatial skills.

Keywords

Spatial ability, science learning, physics, primary school, children

Acknowledgements

This work was funded by an Economic and Social Research Council PhD studentship.

1. Introduction

Spatial thinking involves the representation and transformation of spatial information. The capacity to think spatially is vital in our day-to-day lives; for example, when we pack a suitcase or navigate around an unfamiliar environment. Spatial thinking is also important for science learning. For instance, accurately explaining seasons depends upon understanding the spatial relationship between the sun and earth. As we shall see, research has revealed an association between spatial skills and science achievement in the primary school years. However, it is unclear whether this association is stronger for particular spatial skills or specific aspects of science knowledge, compared to others. Addressing this gap is important because it has theoretical implications for understanding the mechanisms involved in the spatial-science relationship. It also has implications for the development of spatial intervention studies designed to improve children's science learning. This study investigated associations between a range of spatial skills and different types of science knowledge, in the context of a primary school physics lesson.

1.1. Defining spatial thinking

In the current study, we adopt the theoretically-driven '2 x 2' spatial typology (Newcombe, 2018; Uttal et al., 2013). This model crosses two fundamental spatial dimensions: intrinsic-extrinsic and static-dynamic. Intrinsic spatial representations relate to the size, orientation, and shape of individual objects, as well as object parts. Extrinsic spatial representations relate to the relationship between objects, the locations of objects, and the positioning of objects. Dynamic spatial representations involve the movement or transformation of an object, such as a rotation, whereas static representations involve stable objects and no transformations. These two dimensions have a strong empirical basis in the cognitive (e.g., Keehner et al., 2006),

neuroscientific (e.g., Zacks et al., 2003) and confirmatory factor analysis literatures (e.g., Mix et al., 2018). Crossing these dimensions results in four sub-domains: intrinsic-static; intrinsic-dynamic; extrinsic-static; extrinsic-dynamic.

It has been suggested that ‘intrinsic-dynamic’ skills can be divided into ‘rigid’ and ‘non-rigid’ skills (Atit et al., 2013). Rigid transformations (e.g., mental rotation) preserve the distances between the points of an object. During non-rigid transformations (e.g., mental folding), the distance between object points changes during the transformation. This distinction was also taken into account in the choice of spatial tasks included in the current study.

1.2. Knowledge and understanding in science

Content-related knowledge and understanding (e.g., learning about magnetism) is a core element of scientific reasoning (Zimmerman, 2000). During this type of learning, it is necessary to store and retrieve basic elements of knowledge relating to a topic (Mayer, 2002; Wellington, 1988). This scientific factual *knowledge* is *retrieved* from long-term memory in a similar format to its presentation during learning (Mayer, 2002; Vosniadou, 1994) for example, recalling the planet located furthest from the sun.

In contrast, conceptual knowledge involves the interrelationships between elements of knowledge, organised into a knowledge structure (Vaughn, Brown, & Johnson, 2020). Conceptual knowledge is associated with understanding and transfer of learning: the ability to apply learning in a different context. In science, conceptual knowledge is elicited when learners express their understanding of cause-and-effect processes (e.g., explaining how night and day occurs). Many authors consider conceptual knowledge to be organised as a ‘mental model’: an internal representation of a scientific process (Gentner & Stevens, 1983; Johnson-Laird, 1980; Vosniadou, 1994). *Predictions* and *explanations* are often used to measure conceptual knowledge (e.g., Joh et al., 2011; Messer et al., 2008). For example, a child could be asked to

predict which object produces the largest shadow and *explain* why. In the current study, we measured children's factual *knowledge retrieval* and conceptual knowledge. We further subdivided conceptual knowledge into *predictions* and *explanations*.

1.3. Spatial thinking and children's science knowledge

A small number of studies have demonstrated an association between spatial ability and science learning in the primary school years (Tracy, 1990; Harris et al., 2018; Hodgkiss et al., 2018; Mayer et al., 2014; Zhang et al., 2017). Zhang et al. (2017), for example, reported an association between 6-year-olds' mental rotation (intrinsic-dynamic) skills and life science knowledge, controlling for working memory and vocabulary. Spatial perception (intrinsic-static) and spatial visualisation (intrinsic-dynamic) skills were not significantly associated. In addition, Hodgkiss et al. (2018) demonstrated that the spatial skills most strongly associated with 7-11 year old's overall performance on a composite science assessment were mental folding (intrinsic-dynamic) and spatial scaling (extrinsic-static), controlling for vocabulary. Despite also being categorised as an intrinsic-dynamic skill, mental rotation was not a significant predictor. There was also variation by content-related domains. Mental folding performance associated with biology, chemistry and physics scores, spatial scaling associated with biology and chemistry scores, and shape disembedding (intrinsic-static) skills associated with chemistry scores.

Neither study described above investigated whether spatial skills were associated with different types of scientific knowledge (i.e., *knowledge retrieval*, *conceptual predictions*, *conceptual explanations*) within content-related domains (e.g., biology). Making this distinction is important to deepen our understanding of why spatial skills may be associated with learning within these domains.

More specifically, it has been argued that dynamic spatial skills such as mental folding occur through mental simulation of actions (Kosslyn, 1995). A mental simulation is a recreation of the neural circuitry initially involved in the encoding of perceptual or motor information (Hostetter & Alibali, 2010). Considering *knowledge retrieval*, scientific factual information, particularly within physics, is often presented in a visuospatial format (e.g., via visualisations, or supported by sensorimotor actions); or, the content is inherently spatial. Evidence from non-science contexts also indicates that certain types of retrieval involve the mental simulation of the encoding event (Kent & Lamberts, 2008). Stronger dynamic spatial skills may therefore enable children to simulate the spatial representations associated with elements of factual physics knowledge, supporting physics *knowledge retrieval*. However, this has yet to be investigated empirically.

One possible mechanism for the association between spatial thinking and conceptual knowledge is that spatial skills support the construction and manipulation of mental models. Stronger dynamic spatial skills may enable children to simulate the interrelations between elements within a mental model. The findings of Harris et al. (2018) provide some evidence for this mechanism. 6-year-olds' force conceptual knowledge was measured through *predictions* (determining where an object would stop, as a result of a given force) and *inferences* (determining where a force should be added, for an object to reach a given target). After controlling for vocabulary, both were associated with mental folding skills, while mental rotation was not. However, only intrinsic-dynamic spatial skills were measured, and *explanations*, a core element of conceptual knowledge, were not elicited.

To summarise, no study to date has included measures of the different types of science knowledge outlined previously (i.e., *knowledge retrieval*, conceptual *predictions*, conceptual *explanations*), and spatial skill measures mapping onto all sub-domains of the Uttal et al.

(2013) model. Assessing the association between all of these skills would provide fine-grained insights into the extent to which the above simulation mechanisms may play a role.

1.4. Current study

The aim of the current study was to investigate the associations between children's spatial thinking skills and their science *knowledge retrieval* and conceptual knowledge (subdivided into *predictions* and *explanations*). These skills were investigated in the context of a primary school science lesson on sound propagation. Sound propagation was chosen because it was considered that understanding the vibrational process of sound traveling would involve spatial thinking. Additionally, by the age of 10, a significant proportion of children fail to grasp the vibrational model of sound (Mazens & Lautrey, 2003). There is likely to be sufficient variability within children's understanding of this topic, which provides a particularly suitable context for testing the influence of spatial skills. We focused on a whole class lesson to provide standardisation of exposure to instruction, and because it increased ecological validity.

Our first research question was: to what extent do 9 to 10 year olds' spatial skills vary in their degree of association with *knowledge retrieval*, and conceptual knowledge (*prediction* and *explanation* scores), as learning outcomes of a science lesson on sound propagation? We predicted that spatial skills would be associated with both *knowledge retrieval* and conceptual knowledge, due to mental simulation processes. We further predicted that the strengths of these relationships would differ. We expected that that spatial skills would be less associated with *knowledge retrieval* than both *predictions* and *explanations*. This prediction was based on the theory that spatial skills are more critical for the simulation of integrated elements within mental models, i.e. the skills which support conceptual knowledge than *knowledge retrieval*. We also expected that spatial skills would be more strongly associated with *explanations* than

predictions, because conceptual *explanations* require the integration of elements of a mental model more so than conceptual *predictions* (e.g., predicting one outcome).

Our second research question was: which spatial sub-domains, within the Uttal et al. (2013) model, are most strongly associated with children's *knowledge retrieval, prediction and explanation* scores? We predicted that the 'dynamic' spatial skills would be most strongly associated with the measured science knowledge. This finding would support the hypothesis that reasoning about the dynamic sound propagation processes involves dynamic mental simulations.

2. Method

2.1. Participants

Five Year 5 (aged 9-10) classes were recruited, from three UK primary schools, totaling 135 participants. One class was excluded due to a significant lesson interruption and an overnight delay before the post-test. The schools were located in the 30% most deprived neighbourhoods in England, according to the 2015 English Indices of Deprivation, which is based on employment, housing and health provision.

The final sample consisted of 107 participants (mean age: 9.58 years; SD: .33). The gender composition of the sample was 45% female, 55% male. Standard scores from matrix reasoning and vocabulary assessments, described in detail below, were in the average range (matrix reasoning: 25th percentile; vocabulary: 37th percentile). The ethnicity of the sample was 53% white, 26% black, 9% Asian and 19% mixed/other. A power analysis, conducted in G*Power (power = 0.8, α = 0.05) indicated that a sample size of 105 was needed to detect a small to medium effect (f^2 = .12) within the main models (linear regression with vocabulary, prior knowledge and two spatial variables). A small to medium-sized effect was chosen due to the number of spatial measures included, and the likelihood of shared variance between them.

The expectation of a maximum of two spatial predictors in the main models was based on findings from previous research (e.g., Hodgkiss et al. 2018). Ethical approval was granted by the XXX Research Ethics Committee.

2.2. General procedure

Participants first completed cognitive ability measures, one-to-one with the researcher, in a quiet space at their school, for 35 minutes. Testing of each class took approximately 5 days. Within 5 days, participants then completed the prior knowledge assessment, in whole class groups. The first author then immediately after delivered the whole class lesson on sound propagation (60 minutes). After a short break (5 minutes), participants completed the science assessments in class groups.

2.3. Cognitive ability measures

Participants completed the vocabulary and matrix reasoning tasks first in a counterbalanced order. They then completed five spatial tasks: two intrinsic-dynamic skills (a rigid and a non-rigid skill), and one measure for the remaining three sub-domains, in a counterbalanced order. All computerised tasks (mental folding, mental rotation, spatial scaling and arrival judgement) were coded in Psychtoolbox for Matlab, and presented on a 13" Macbook laptop. Accuracy was recorded for all spatial tasks.

2.3.1. Vocabulary. The expressive vocabulary subtest of the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999) was administered according to the manual. Participants gave up to 22 word definitions, which were scored between 0 and 2, depending on its completeness. Testing was discontinued after three consecutive scores of zero. A score of 3 was added for the picture items not administered for this age group, resulting in a total possible score of 47.

2.3.2. Fluid reasoning ability. The Matrix reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999) was administered according to the manual. Participants select the option that best completes a series. Participants completed a maximum of 30 items, which each gave a maximum score of 1. Testing was discontinued after three incorrect responses

2.3.3. Visual discrimination task (intrinsic-static skill). Participants completed the discrimination subtest of the Test of Visual Perceptual Skills (TVPS; Gardner, 1996). Participants were shown a black 2D target shape and five geometric shapes. The participant selected the shape that matched the target shape. The task includes 16 items; each correct answer gave a score of 1. The participant completed two practice items. If they failed on a first attempt, they were given a maximum of one further attempt to answer each practice item.

2.3.4. Mental folding (non-rigid intrinsic-dynamic skill). In this task (Harris et al., 2013), participants determined what a target shape would look like after being folded. Participants selected from four options (Figure 1). Participants first completed two practice items. Participants were given a card version of the shape to check their answer for the first practice item. Answers to the practice questions were checked by a researcher. If a participant gave an incorrect response, they were given one further attempt at each practice item. All participants passed the practice items. Practice items were followed by 14 experimental trials; each correct answer gave a score of 1.

Figure 1: Mental folding trial (answer is c)

2.3.5. 2D mental rotation (rigid intrinsic-dynamic skill). Mental rotation ability was assessed with the rotation sub-test of Thurstone's Primary Mental Abilities Test (Thurstone, 1948). Participants determined which one of four shapes would with a target shape to form a square (see Figure 2). Participants completed a shortened version which included 8 items; each correct answer gave a score of 1. Participants completed two practice items. If they failed on a first attempt, participants were given a maximum of one additional attempt to answer each practice item. All participants passed the practice items.

Figure 2: Mental rotation trial (answer is b)

2.3.6. Spatial Scaling (extrinsic-static skill). The scaling task used in the current study (Gilligan et al., 2018) required participants to find corresponding locations on two maps, when the maps differed in size by a scaling factor. Participants viewed four treasure maps, on a computer screen. On each map, a treasure location was indicated by a black square. Participants were also presented with one printed treasure map (Figure 3). They were asked to determine which of the four computer treasure maps displayed the treasure location in the same position as the larger printed map.

Figure 3: Spatial scaling trial (answer is a)

Printed maps were either unscaled (1:1), or were scaled to either 1:2 or 1:4, relative to the computer maps. Participants completed 18 trial items; each correct answer gave a score of 1. Six items were presented at each scale factor. For half of the main items, the map was divided into 6 x 6 (larger) grid sections. For the other half of the main items, the map was separated into 10 x 10 (smaller) sections. Two practice items were completed. Practice items needed to be answered correctly before proceeding. If, on their first attempt, participants did not get the answer correct, they were given feedback and one further opportunity to complete the item. Only participants who correctly answered one or more on their first attempt continued to the main trials; all participants achieved this.

2.3.7. Arrival Judgement Task (extrinsic-dynamic spatial skill). This task required judgment of relative motion and was adapted from a paradigm developed for adults by (Hunt et al., 1988). Participants were presented with two vertical lines: the start and finishing line of a race (Figure 4). Four squares appeared vertically at varying distances from the starting line. The squares moved towards the finishing line, at varying speeds. When the objects reached the middle of the screen, they disappeared. If they had continued traveling at the same speed, three of the squares would have arrived at the finishing line simultaneously, and one would have arrived before. Participants determined which square would have won the race. Participants completed 20 trials split into 5 difficulty levels; each correct answer gave a score of 1. Difficulty levels were varied by decreasing the difference in arrival time between the ‘winning’ square and the other squares, by varying the objects’ speed and starting points. Before the main trials, participants completed two practice items. If they failed on a first attempt, they were given a maximum of one further attempt to answer each practice item. All participants passed the practice items.

Figure 4: Arrival judgment task sequence (item 1, level 1)

2.4. Prior knowledge assessment

To assess prior knowledge, participants were shown an illustration of a girl listening to a ringing bell. Participants wrote an explanation of how she was able to hear the sound. Explanations were scored 0-3, corresponding to: no understanding, partial understanding, established understanding or good understanding. Table 1 provides examples of responses. A second coder scored a random 20% of the responses which indicated high inter-rater reliability (intraclass correlation = .98).

Table 1: Coding scheme for prior knowledge assessment.

Score and description	Example response
Score 0: No evidence of relevant prior knowledge. Irrelevant / entirely incorrect response.	She hears a loud noise because the bell is tolling
Score 1: Some evidence of prior knowledge. No reference to what is vibrating.	I think the sound is caused by vibrations
Score 2: Evidence of established prior knowledge. Reference to what is vibrating.	Because when the little ball hits the bell, the bell vibrates
Score 3: Evidence of good prior knowledge. Reference to what is vibrating, and at least one additional causal element.	The bell rings and vibrates, and then the sound travels to her ears, and there are small hairs inside her ears which vibrate and send a message.

2.5. Science lesson

The first author, a qualified primary school teacher, delivered the same science lesson to each class. It lasted one hour, with a short break in the middle. The first part of the lesson introduced the vibrational model of sound. The second part of the lesson focused on how the vibrational model applies to sound traveling through solids, liquids, and gases. The lesson plan was discussed before the study with a teacher of this age range.

The lesson included activities which children of this age would typically encounter: verbal instruction, questioning; and videos, text, and images presented on an interactive whiteboard. The videos included instructional information as well as visual models (e.g., flickering candles to demonstrate air vibrating as a result of sound from a speaker). There were also brief practical activities (e.g., feeling own vocal cord vibrating) and a small group activity (agreeing on the correct causal sequence of images and text via discussion). See ‘further details about lesson content’ in the supplementary material for more information.

2.6. Post-test (science assessment)

The post-test consisted of two paper and pencil assessments. One assessment included *knowledge retrieval* questions and the second included scenarios, which included *predictions* and *explanations*. To reduce the impact of literacy ability, the researcher read aloud each question. The time given to complete each question was approximately 1 minute for *knowledge retrieval* and 5 minutes for conceptual knowledge. Participants completed the questions silently and independently.

2.6.1. Knowledge retrieval questions. The six knowledge retrieval questions are provided in Table 2. Five questions had a maximum score of one and one question had a possible score of two, resulting in a maximum score of 7.

Table 2: *Knowledge retrieval* questions.

-
- 1) As you move further away from an object making a sound, the sound_____.

☐ Becomes quieter ☐ Becomes louder ☐ Stays as loud as it was
 - 2) Which of the following type of wave travels the fastest?

☐ Light ☐ Sound
 - 3) Tick all of the following types of medium which sound **can** travel through

☐ Solid ☐ Liquid ☐ Gas ☐ Vacuum
 - 4) Sounds are made when objects_____.
 - 5) Another name for a sound wave is a _____ wave.

☐ Compression ☐ Surface ☐ Transverse
 - 6) Give one example of a use for echo_____.
-

2.6.2. Conceptual knowledge questions. Participants then completed 8 questions, which assessed their conceptual knowledge via predictions and explanations. Each conceptual knowledge question was based around a scenario that involved sound traveling. Two levels of difficulty were included. The first four questions were close to the scenarios discussed in the lesson but were still unfamiliar. The remaining four scenarios required the application of understanding to more novel scenarios. For each question, participants first gave a written prediction (e.g., what do you think would happen if...?). Participants then explained their prediction. Table 3 and Table 4 include an example of a conceptual knowledge question at each difficulty level. See Table S1 for the complete set of questions and Figure S1 for an example as presented to participants.

Table 3: Example of conceptual knowledge questions (lower difficulty level: question 1)

Scenario	Prediction	Explanation
Josh stood in his classroom next to the door. Michael then closed the door. Josh then shouted to Michael on the other side of the door.	Imagine you were Michael. Predict what happened when Josh shouted with the door closed.	Explain as fully as you can how this happened, starting from the moment Josh shouts. [initial starting prompt given]: Josh shouts

Table 4: Example of conceptual knowledge questions (higher difficulty level: question 5)

Scenario	Prediction	Explanation
Lydia wants to soundproof her room so that her neighbours, who live next door, are not disturbed by her music.	Predict which material would be the best at soundproofing (the best at blocking the sound and reducing how much sound travelled to her neighbours).	Use your understanding of how sound travels through different mediums to explain why you think this, as fully as you can. Write about both types of material.
She first covers the wall between her and the neighbours in carpet tiles, plays her music and then asks her neighbour to measure the sound.	Do you think wooden tiles would be better, carpet tiles would be better, or they would both be as good as each other, for soundproofing?	[initial starting prompts given]: When she uses wooden tiles...
After that, she removes the carpet tiles and then covers the wall with wooden tiles instead, and her neighbour measures the sound again.		When she uses carpet tiles...

2.6.3. Scoring of conceptual knowledge questions. The *prediction* element of each scenario was coded as either correct or incorrect, using a selection of acceptable answers. *Explanations* were scored using a coding scheme for each scenario, which gave credit for depth of conceptual understanding. For four of the questions (Q1, Q2, Q3 and Q8), it was possible to score up to 3 on each *explanation*. Example *prediction* and *explanation* responses for question one (lower level of difficulty; previously presented in Table 3) are displayed in Table 5 and 6. For four questions (Q4, Q5, Q6 and Q7), the *explanation* response was broken down into two parts. In these questions, it was possible to score a maximum of two per part. Example *explanation* responses for question 5, which included a two-part *explanation*, are included in the Table S2.

A random 20% of the conceptual knowledge assessments (*predictions* plus *explanations*) were scored by a second coder, which resulted in an overall high inter-rater reliability (intraclass correlation: $r = .98$). Internal reliability of the conceptual knowledge questions, with the *prediction* and *explanation* for each conceptual knowledge question

included as separate items, was good ($\alpha = .810$), as was the reliability for the *explanations* alone ($\alpha = .795$). Reliability of the *predictions* ($\alpha = .556$) and *knowledge retrieval* items ($\alpha = .529$) was lower.

Table 5: Example responses for *prediction* element of question one

Score	Example response
0	‘it would not have opened’
1	‘Michael could still hear Josh’

Table 6: Example responses for *explanation* element of question one

Score	Description	Example responses
0	Irrelevant answer; incorrect or incomplete response.	‘Because something is blocking it.’
1	One element (with vibrational mechanism). Two elements (path and no clear vibrational mechanism).	‘because the door vibrates’ ‘the particles in the door vibrate on the other side’ ‘the sound travels through the air and then through the door’
2	Two elements (with vibrational mechanism). One element (with vibrational mechanism), with one or more additional element referring to path (without vibrational mechanism).	‘the vibration travelled through the door and then vibrates in Michael’s ear’ ‘the particles vibrate and the sound travels to Michael’s ears’
3	Three elements (with vibrational mechanism).	‘The air particles vibrate, hitting more air particles next to it. The sound then travels through the solid door. The air particles vibrate around his ear and then his eardrum vibrates and sends a message to the brain’

3. Results

3.1. Analysis strategy

Analysis of variance (ANOVA) was first used to check for any effects of school class grouping. To analyse the association between the spatial thinking tasks and science variables, we used Pearson's correlations, partial correlations, linear regression and commonality analysis. We controlled for vocabulary and prior knowledge in the partial correlations, primary linear regression models and commonality analyses. Vocabulary was controlled for because this variable also correlates with spatial skills and science reasoning (e.g., Zhang et al. 2017). Prior knowledge was controlled for to align the findings more closely with the lesson's learning outcomes. Secondary linear regression models were also carried out, in which non-verbal reasoning ability was also controlled for. These represent a more conservative assessment of associations between spatial thinking and science.

Four participants were missing science assessment data due to being absent from the lesson. One participant was missing prior knowledge data due to administration error. For task-based analysis (reliability and descriptive statistics), these participants were excluded. For other analyses, missing data were replaced with the variable mean, to maximise statistical power. Mean replacement was used rather than multiple imputation because the two linked analyses (i.e., linear regression and commonality analysis) require a single data set rather than pooled results. Multiple imputation generates the same pattern of results (see 'multiple imputation results' section of supplementary material).

3.2. Descriptive statistics

Descriptive statistics were first calculated to provide an overview of performance across tasks (Table 7). There were three science variables. These were a *knowledge retrieval* score (with a maximum score of 7), and two conceptual knowledge scores: *predictions* (with a maximum

score of 8); and *explanations* (with a maximum score of 28). A total conceptual knowledge score was also calculated, consisting of *predictions* plus *explanations* for each scenario (derived from a maximum score of 36). Total conceptual knowledge scores were used only to indicate overall performance. As expected, scores on the conceptual knowledge questions were lower (24% mean accuracy) than *knowledge retrieval* (66% mean accuracy). Looking in detail at conceptual knowledge, although prediction scores were relatively high (61% mean accuracy), *explanation* scores were low (14% accuracy). See Figures S2-S6 for distribution plots for each science variable.

Table 7: Descriptive statistics

Measure	Max	M	SD	Range
Prior knowledge	3	.98	.87	0-3
<i>Knowledge retrieval</i>	7	4.63	1.62	0-7
Conceptual total (<i>prediction</i> + <i>explanation</i>)	36	8.67	5.30	0-29
<i>Prediction</i> total	8	4.84	1.79	0-8
<i>Explanation</i> total	28	3.82	4.06	0-21
Matrix reasoning raw score	30	12.64	4.44	5-27
Matrix reasoning T-score (standard)		42.8	9.65	28-80
Vocabulary raw score	47	23.85	5.81	11 - 42
Vocabulary T-score (standard)		46.9	10.40	14 - 78
I-D(R) (mental rotation task)	8	6.39	1.47	1-8
I-D(NR) (mental folding task)	14	8.59	2.84	3-14
I-S (discrimination task)	16	9.81	2.39	5-15
E-S (scaling task)	18	12.42	2.76	6-17
E-D (arrival judgment task)	20	12.79	2.62	3-19

Note. I-D (R): intrinsic-dynamic, rigid; I-D (NR): intrinsic-dynamic, non-rigid; I-S: intrinsic-static; E-S: extrinsic-static; E-D: extrinsic-dynamic. A T-score of 50 for Matrix Reasoning and Vocabulary represents the 50th percentile.

3.3. Analysis of school class

A preliminary ANOVA was carried out to investigate the possible effect of school class grouping on the science measures. This revealed no significant effect of class grouping on *knowledge retrieval* scores ($p = .815$, $\eta_p^2 = .009$), *prediction* scores ($p = .159$, $\eta_p^2 = .049$), or *explanation* scores ($p = .562$, $\eta_p^2 = .020$). This variable was not considered further.

3.4. Correlations and partial correlations

Pearson's correlations were first employed, between the spatial tasks, IQ and science measures (Table 8, upper triangle). Partial correlations, controlling for vocabulary and prior knowledge were also calculated between the spatial tasks and science measures (Table 8, lower triangle). Knowledge retrieval scores had small, significant correlations with spatial scaling and arrival judgment only. However, after controlling for vocabulary and prior knowledge, no significant correlations remained. Prediction scores had small, significant correlations with mental rotation and arrival judgment. A significant partial correlation remained with mental rotation only. Explanation scores had small or moderately sized, significant correlations with all spatial thinking tasks. Significant partial correlations remained for mental folding, mental rotation and visual discrimination only.

3.5. Primary regression analysis

We then ran linear regression analyses to determine the amount of variance in the science measures accounted for by the spatial tasks. Analysis of Cooke's Distance revealed no values greater than 1, for any variable, which indicated that the regression models were not biased by individual cases.

Table 8: Correlations (top right) and partial correlations (controlling for vocabulary and prior knowledge [bottom left]) between main study variables.

	Science Measures				WASI IQ Measures		Spatial Thinking Measures					
	Age	PriorKn	KnoRet	Predi.	Explan.	Matrix	Vocab	Folding	Ment.Rot	Vis.Disc	Scal.	Arrival
1. Age (months)		.02	.13	.03	.14	-.01	.06	-.10	-.07	-.11	.01	-.06
2. Prior knowledge			.38**	.32**	.47**	.28*	.32**	.17	.08	.20*	.18	.27*
3. <i>Knowledge retrieval</i>				.46**	.51**	.23*	.51**	.17	.18	.14	.25*	.21*
4. <i>Predictions</i>					.58**	.26*	.40**	.19	.25*	.19	.09	.24*
5. <i>Explanations</i>						.37**	.49**	.36**	.26*	.34**	.29*	.29*
7. Matrix reasoning							.28*	.44**	.36**	.43**	.50**	.40**
8. Vocabulary								.03	.07	.21*	.20*	.12
9. Mental folding			.14	.17	.36**				.49**	.63**	.44**	.34**
10. Mental rotation			.16	.24*	.25*					.50**	.37**	.14
11. Visual discrimination			.00	.08	.24*						.55**	.23*
12. Spatial scaling			.15	-.02	.19 [†]							.26*
13. Arrival judgement			.13	.17	.19 [†]							

* $p < .05$ ** $p < .001$ † $p = .051$ PriorKn: prior knowledge; KnoRet: *knowledge retrieval*; Predi.: *predictions*; Explan: *explanations*; Matrix: matrix reasoning
Vocab = vocabulary; Folding: mental folding; Mental.Rot = mental rotation; Vis.Disc = visual discrimination; Scal = spatial scaling; Arrival: arrival judgement

Primary regression analyses included vocabulary and prior knowledge as control variables, which were entered in model 1 in all analyses. To construct parsimonious models, spatial tasks were only included if they had significant partial correlations with science measures. Spatial tasks were then entered hierarchically and only retained if they significantly improved the model. The order of entry for the spatial variables was based on the strength of prior empirical evidence base, outlined in the introduction: mental folding, mental rotation, spatial scaling, visual discrimination, arrival judgement.

For *knowledge retrieval*, vocabulary and prior knowledge were entered only. Vocabulary and prior knowledge collectively accounted for 31% of the variance in *knowledge retrieval* scores (Table 9, analysis 1). Considering *predictions* (Table 9, analysis 2), vocabulary and prior knowledge entered in model 1 accounted for 20% variance. Mental rotation added in model 2 accounted for an additional 5% variance. For *explanations* (Table 9, analysis 3), vocabulary and prior knowledge accounted for 35% of the variance in scores, in model 1. Mental folding accounted for an additional 9% variance in scores in model 2. Neither mental rotation ($F < 1$, $p = .338$) nor visual discrimination ($F < 1$, $p = .827$) significantly improved the model when added separately in *explanations* model 3.

3.6. Commonality analysis

To provide less conservative estimates of effect sizes for the primary analyses, commonality analysis was then used to partition each r^2 value accounted for by the predictor variables into unique and shared variance (e.g., Cragg et al., 2017). This analysis was run using the variables included in the primary analyses (analyses 2 and 3) with an SPSS script (Nimon, 2010). See ‘further details about commonality analysis’ section of the supplementary material for more information.

Table 9: Multiple regression analyses with science scores as dependent variables

	b	SE	β	<i>t</i>	<i>p</i>	<i>F</i>	<i>df</i>	<i>p</i>	<i>R</i>²	ΔR^2
<i>Analysis 1 (knowledge retrieval)</i>										
Model 1										
Vocabulary	.12	.024	.43	5.05	< .001					
Prior Knowledge	.45	.163	.24	2.79	.006	23.51	2, 104	< .001	.31	.31
<i>Analysis 2 (conceptual predictions)</i>										
Model 1										
Vocabulary	.10	.03	.33	3.60	< .001					
Prior Knowledge	.40	.18	.20	2.19	.031	13.19	2, 104	< .001	.20	.20
Model 2										
Mental Rotation	.24	.10	.21	2.48	.015	6.15	1, 103	.015	.25	.05
<i>Analysis 3: (conceptual explanations)</i>										
Model 1										
Vocabulary	.27	.05	.38	4.90	< .001					
Prior Knowledge	1.40	.37	.30	3.80	< .001	28.02	2, 104	< .001	.35	.35
Model 2										
Mental Folding	.42	.11	.30	4.00	< .001	15.74	1, 103	< .001	.44	.09

Note: Beta values refer to the final model with all variables included

Table 10 reveals that mental rotation accounted for a slightly higher proportion of variance in *predictions*, when shared variance with other variables was included (i.e., .04 unique to mental rotation vs .07 variance shared between mental rotation and other predictors). This was accounted for by small amounts of shared variance with vocabulary, prior knowledge, and variance common to all variables.

Table 10: Commonality analysis for *predictions*.

	Variance explained
Unique to mental rotation	.04
Unique to vocabulary	.09
Unique to prior knowledge	.04
Common to mental rotation and vocabulary	.01
Common to mental rotation and prior knowledge	.01
Common to vocabulary and prior knowledge	.05
Common to all	.01
Total	0.25

For *explanations*, mental folding accounted for .14 variance when variance shared with other variables was included (see Table 11), versus .09 unique variance. The majority of shared variance was between mental folding and prior knowledge (.03).

Table 11: Commonality analysis for *explanations*.

	Variance explained
Unique to mental folding	.09
Unique to vocabulary	.13
Unique to prior knowledge	.08
Common to mental folding and vocabulary	-.01
Common to mental folding and prior knowledge	.03
Common to vocabulary and prior knowledge	.10
Common to all	.02
Total	.44

3.7. Secondary regression analysis

Two sets of more conservative linear regression analyses were also run. First, analyses were run that also included the matrix reasoning task in model 1, to control for fluid reasoning ability. After adding matrix reasoning, mental rotation was still significantly associated with *prediction* scores ($\beta = .20$; $\Delta F [1,102] = 4.56, p = .04$), and mental folding was significantly associated with *explanation* scores ($\beta = .27$; $\Delta F [1,102] = 10.58, p = .002$). Second, an analysis was run for *explanations* in which the remaining significant spatial tasks from the partial correlation analysis were entered simultaneously in model 2. This contrasts with the primary analyses in which the spatial tasks were added hierarchically and retained only if they significantly improved the model. With mental rotation and visual discrimination in model 2, mental folding was still significantly associated with *explanations* when it was then entered in model 3 ($\beta = .26$; $\Delta F [1,101] = 6.74, p = .011$).

4. Discussion

A growing body of research supports the association between spatial thinking and science learning and reasoning in the primary school years. However, little is known about the specific mechanisms involved in this relationship. The goal of the present study was to investigate the association between spatial skills and content-related physics knowledge in primary school aged children, in the context of a science lesson on sound propagation.

We first investigated whether the strength of this association varied by type of physics knowledge (*knowledge retrieval*, or conceptual knowledge, which was further divided into *predictions* and *explanations*). The results showed that, after controlling for vocabulary skills, children's spatial thinking skills were not significantly associated with *knowledge retrieval*. However, spatial skills significantly associated with *predictions* and *explanations*: the association was stronger for *explanations* ($r^2 = 9-13\%$) than *predictions* ($r^2 = 5-7\%$). The results therefore indicate the strength of association does vary by physics knowledge type.

The findings suggest that, for this physics topic, spatial thinking is more important for conceptual knowledge than factual knowledge. There was no evidence to support the hypothesis that spatial skills support the retrieval of individual units of information via mental simulation. These findings more so support the hypothesis that spatial skills are particularly beneficial for the simulation of integrated elements of conceptual knowledge within mental models. The findings further suggest that spatial thinking is more important for conceptual *explanations* than *predictions*. This could be because generating a *prediction* required less coordination between different elements of the mental model. The *predictions* often required participants to describe the outcome of a series of events, focusing on a single aspect of the model. In contrast, conceptual *explanations*, which involve a sequence of linked points, required that participants use and coordinate between different elements within the model to a

greater extent. This coordination may also require a greater degree of piecemeal mental simulation. For example, a mental simulation of the causal chain of events involved in hearing a sound may begin with an object being struck, followed by the vibration of the object, then the air.

We also investigated which of the Uttal et al. (2013) sub-domains was the most strongly associated with each type of physics knowledge. This demonstrated that the intrinsic-dynamic domain was the most strongly associated with both *predictions* and *explanations*. However, mental rotation was more strongly associated with *predictions*, while mental folding was more strongly associated with explanations. This finding may be due to the previously outlined rigid / non-rigid distinction. One possible interpretation is that the stronger association between mental folding and explanations is due to the greater degree of flexibility required for non-rigid transformations (i.e., the distances between points of an object change). This spatial flexibility may be more useful for manipulating the mental model, which is more important for generating explanations for the given scenarios. These findings only partly support the theory that dynamic spatial skills support the dynamic simulation of processes. The arrival judgement task, an extrinsic-dynamic skill, was not associated with any science measure, within the final models. It may be that the object-based transformation processes involved in intrinsic-dynamic skill, described above, are particularly important.

These findings are in line with research by Hodgkiss et al. (2018) who found that intrinsic-dynamic skills (mental folding) were associated with 7-11 year old's physics achievement. The current findings extend this work by identifying which type of content knowledge is more closely associated with physics reasoning. The findings are also in line with findings from Harris et al. (2018), who reported that mental folding ability is associated with 6 year old's judgments about force and motion. One difference, in both cases, was our finding that mental rotation was significantly associated with *predictions*. Both Hodgkiss et al. (2018) and Harris

et al. (2018) found that mental folding, but not mental rotation, was associated with the respective physics outcomes. The difference may lie in the mental rotation task in this study, which required construction (i.e., finding the piece that fits to make a whole), combined with the core mental rotation transformation. It may be that the combination of these processes was supportive of the physics reasoning in this study. For example, the ability to predict which shape would fit to make a whole after rotation was perhaps supportive of simulations related to elements making up wholes within the lesson (i.e., vibration of particles that make up a solid object).

The current findings have implications for supporting children's science learning. Given the observed associations between spatial thinking skills and science reasoning, a further logical question is whether training children's spatial skills might result in improvements in science outcomes. A meta-analysis of studies by Uttal et al., (2013) revealed that that spatial training results in moderately sized, durable improvements in spatial skills. However, there is limited research to date investigating possible far transfer effects (e.g., training mental rotation training improves science learning). There are a few exceptions in science with adults (e.g., Sanchez, 2012) and mathematics with younger children (e.g., Gilligan et al., 2020). Future intervention studies are needed to confirm that the associational evidence observed in the current study represents a causal relationship. The findings of the current study suggest that such intervention studies should include both mental folding and rotation, and might also focus on training non-rigid, intrinsic dynamic transformations while learning about the conceptual mechanisms involved in physical process.

It is also worth noting that vocabulary scores were strong predictors of each science variable. This is not surprising, in the case of explanations in particular, given that the expression of explanations is fundamentally a verbal process. These findings add to the broader

evidence base on the importance of vocabulary in science learning and reasoning (e.g., Townsend et al. 2012).

There are limitations and caveats to consider alongside the above conclusions. First, some of the science measures (e.g., *knowledge retrieval*) had lower Chronbach's alpha reliability scores than would be ideal. This is likely due to the relatively low number of items, combined with the diversity of content coverage within the respective measures. Second, it would have been useful to measure children's engagement in the lesson, as a further covariate. Finally, the findings are limited to a single physics topic. The intention was to investigate a specific hypothesis in depth since this is typically how children encounter these topics in the classroom. Nevertheless, further research is needed to explore whether these patterns of association are observed in other areas of the primary school physics curriculum.

In conclusion, the current study provides further insights into the specificity of the associations between spatial thinking and physics learning in the primary school years and the mechanisms that may underpin it. The findings indicate that spatial skills are significantly associated with 9 to 10 year old's conceptual understanding of sound, but not with the retrieval of individual pieces of knowledge. Within the domain of conceptual understanding of sound, spatial skills are more strongly associated with children's *explanations* than *predictions*. In addition, we showed that intrinsic-dynamic spatial skills are most strongly associated with these outcomes. However, there were also some differential associations between mental folding/mental rotation and *predictions/explanations*. A strength of these findings is that they are embedded within an ecologically valid context. These findings can inform the design of future experimental intervention studies, which can potentially improve science learning for primary school aged children.

5. Acknowledgements

This work was funded by an Economic and Social Research Council PhD studentship.

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