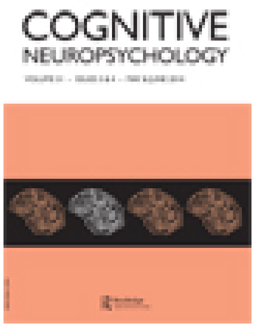

Cognitive Neuropsychology

ISSN: 0264-3294 (Print) 1464-0627 (Online) Journal homepage: http://www.tandfonline.com/loi/pcgn20

Cognitive processes in spatial mapping: Evidence from a developmental spatial deficit

Miles Hatfield, Caroline Reilhac, Hannah Cowley, Elizabeth Chang & Michael McCloskey

COGNITIVE NEUROPSYCHOLOGY, 2017
https://doi.org/10.1080/02643294.2017.1389708

Cognitive processes in spatial mapping: Evidence from a developmental spatial deficit

Miles Hatfield, Caroline Reilhac, Hannah Cowley, Elizabeth Chang and Michael McCloskey

Department of Cognitive Science, Johns Hopkins University, Baltimore, MD, USA

ABSTRACT
We report a case study of an adolescent girl (N.K.Y.) with a developmental deficit affecting spatial processing. In a simple *spatial mapping* task, N.K.Y. shows a striking dissociation: She succeeds in one variant of the experiment in which the stimuli are objects, but struggles in a structurally identical task with people as stimuli. We present evidence that this dissociation stems from a tendency to automatically adopt the spatial perspective of other people, but not objects—a phenomenon also observed in neurotypical individuals. When adopting another person's perspective, N.K.Y. imagines herself in the other's position, representing the other's left and right as if it were her own. N.K.Y.'s deficit in relating left–right information to her own body then disrupts her performance. Our results shed light on the nature of N.K.Y.'s deficit as well as the cognitive operations involved in spatial perspective taking.

ARTICLE HISTORY
Received 2 April 2017
Revised 28 September 2017
Accepted 29 September 2017

KEYWORDS
Perspective taking; developmental deficit; spatial compatibility

Introduction

A wide range of cognitive tasks require establishing a mapping—that is, a set of correspondences—between distinct spatial regions. For example, in using a diagram to assemble a piece of furniture, one must establish correspondences between locations and dimensions within the space of the diagram, and locations and dimensions in the environmental space where the furniture is being assembled. Other examples of spatial mapping tasks include copying a picture, imitating another person's gestures, and, of course, using a map to navigate an environment such as a city or university campus.

Spatial mapping processes are also involved in phenomena studied extensively in the literature on spatial cognition and representation. For example, the computation of heading direction, a core component of navigation (Klatzky, 1998), involves establishing the appropriate mapping between one's own body and the environment. The acquisition of the concepts of left and right in children involves establishing correspondences between one's own and the other's sides (Shusterman & Li, 2016). Finally, an important debate in the literature on reference frames concerns whether putatively allocentric representations are in fact egocentric representations that have been mapped onto an external object (Filimon, 2015; for overviews of frame-of-reference concepts see, e.g., Levinson, 1996; McCloskey, 2001).

In most, if not all, spatial mapping tasks, successful performance hinges on attending to relevant spatial information while ignoring irrelevant spatial properties. Consider a child who, in the course of learning to write, is attempting to copy a capital P. The child must attend to the fact that the loop is to the right of the vertical stroke and reproduce this spatial relationship in her copy. However, the feat must be accomplished in the presence of potentially conflicting sources of left–right information that are not relevant to the task. For instance, the stimulus letter as a whole may be printed to the left of the space in which the copy is to be made. Failure to separate relevant from irrelevant spatial properties, and treat them accordingly, could interfere with performance.

In the present study we examined spatial mapping performance in an adolescent girl with a developmental spatial deficit, using very simple tasks of the sort illustrated in Figure 1. The participant views a source stimulus, here shown as a white rectangle, positioned to the left or right of a centrally located target stimulus. A small object, which we refer to as the stimulus marker, is placed on either the left or right side of the source. The participant's task is to place an

CONTACT Miles Hatfield hatfield@cogsci.jhu.edu

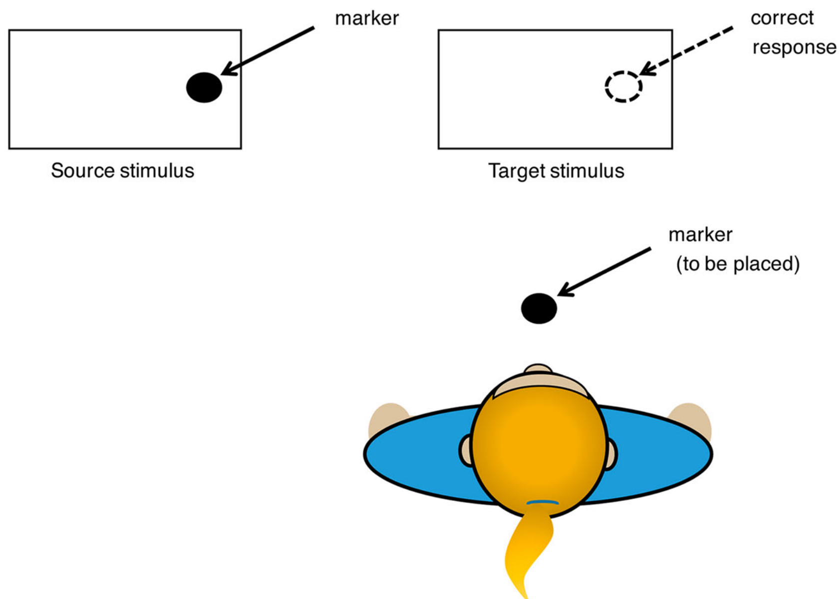

Figure 1. The spatial mapping task (Experiment 1a). A "source" stimulus is presented to the left or right of a "target" stimulus, with a marker object placed on its left or right side. The observer's task is to place another marker object on the corresponding left or right side of the target. The correct response for the current trial is shown with dotted lines. [To view this figure in colour, please see the online version of this Journal.]

identical response marker on the left or right side of the target stimulus, so as to make it match the source. For example, in Figure 1 the stimulus marker is on the right side of the source, so the participant should place the response marker on the right side of the target.

This task requires establishing a spatial mapping between source and target, specifying how the sides of the source correspond to the sides of the target. The mapping must be set up in the presence of potentially interfering spatial information: The source as a whole is positioned to the left or right of the target, yet its position plays no role in determining the correct response. The task is therefore a spatial compatibility task (Kirkham & Tipper, 2015; Kornblum, Hasbroucq, & Osman, 1990; Kornblum, Stevens, Whipple, & Requin, 1999), in which the observer must make a response to spatial information (the left–right position of the marker relative to the source), when that information may conflict with other information present in the task (the left–right position of the source relative to the target).

The same basic task structure may be realized in many different ways. For example, various sorts of stimuli may be used as sources and targets: rectangles, as in Figure 1, or 3-D objects, or even people. These variations in stimuli do not affect the logical structure of the task (i.e., which spatial properties are relevant, and how these properties determine the correct responses) and would seem to create only minor, superficial variants of the same basic task.

However, seemingly minor stimulus variations could significantly change the way observers perform the task, even when the logical structure remains the same. In this article we describe one such case, in which a difference in stimuli between otherwise identical tasks leads to dramatic effects on an individual's performance. We present results from N.K.Y., an adolescent girl with a developmental deficit affecting spatial processing. N.K.Y. succeeds at one variant of a spatial mapping task in which the source and target stimuli are objects (as in Figure 1), but has difficulty in a structurally identical task when the sources and targets are people. We explore this dissociation in a series of experiments, offering an interpretation that sheds light not only on N.K.Y.'s spatial deficit, but also on the normal cognitive processes underlying performance in spatial mapping tasks. The results of this investigation have implications for a range of topics in spatial cognition, including reference frames, spatial perspective taking, and the representation of position.

Case report

N.K.Y. is a right-handed girl (11–13 years old during the present study) with no history of neuropathology. She presents with developmental deficits affecting spatial processing, as well as some aspects of language and motor skills. N.K.Y. has been diagnosed with attention-deficit/hyperactivity disorder (ADHD), but the deficit is well controlled with medication, and she had no difficulty maintaining focus during our testing.

As an infant, N.K.Y. met motor milestones at the low end of the normal range, standing at 12 months and walking at 15 months, and she also suffered speech delays, not speaking in full sentences until approximately 4 years of age. A 2013 neuropsychological assessment at age 10;9 revealed below-average speech and language skills (age equivalents on standardized tests at approximately 5 or 6 years old). Despite her language deficiencies, N.K.Y. had no difficulty conversing with us during testing sessions, showing good comprehension as well as an ability to express her ideas and opinions clearly.

N.K.Y. has normal visual acuity and showed no signs of neglect or visual field defects, but has difficulties with visual memory and visuospatial cognition. In copying pictures or shapes she often struggles, showing a tendency to left–right reverse, misorient, or omit elements, especially when stimuli include oblique lines. Figure 2 displays two of N.K.Y.'s copies. In the complex shape on the top left, many details are incorrectly copied or omitted—for instance, the outer diamond shape is copied as a triangle. Although N.K.Y. performed better for the simpler shape on the right, the "tail" of the shape is still copied with an incorrect orientation. Her errors are not concentrated on one side or otherwise suggestive of neglect; rather, they suggest difficulty in parsing or assembling the various segments of a shape or figure.

With respect to high-level vision, N.K.Y.'s object recognition appears intact despite her visuospatial difficulties. On the Boston Naming Test she produced the correct name for only 35 of the 60 items, but her responses to the remaining items clearly demonstrated that she recognized the picture stimulus (e.g., stethoscope: "heart checker"; trellis: "keeps up flowers"). On reading tasks her performance is below grade level but demonstrates intact visual processing: She was 100% correct in visual letter identification tasks, and she read high-frequency words without difficulty (e.g., 100% correct on the first 60 items of the Test of Word Reading Efficiency, TOWRE, Word List–Form A; Torgesen, Rashotte, & Wagner, 1999).

We assessed N.K.Y.'s comprehension of the terms "left" and "right" using the Test of Right–Left Orientation (Benton, Hamsher, & Spreen, 1983). This test involves pointing to or using left and right body parts when prompted by the experimenter (e.g., "raise your right hand"; "point to my right eye"). N.K.Y. had difficulty identifying both her own and the experimenter's left and right sides, scoring 15/24 correct (62.5%) for her own body, not significantly different from chance performance ($p = .15$, binomial test), and at chance (6/12) for the left and right of an examiner seated facing her.

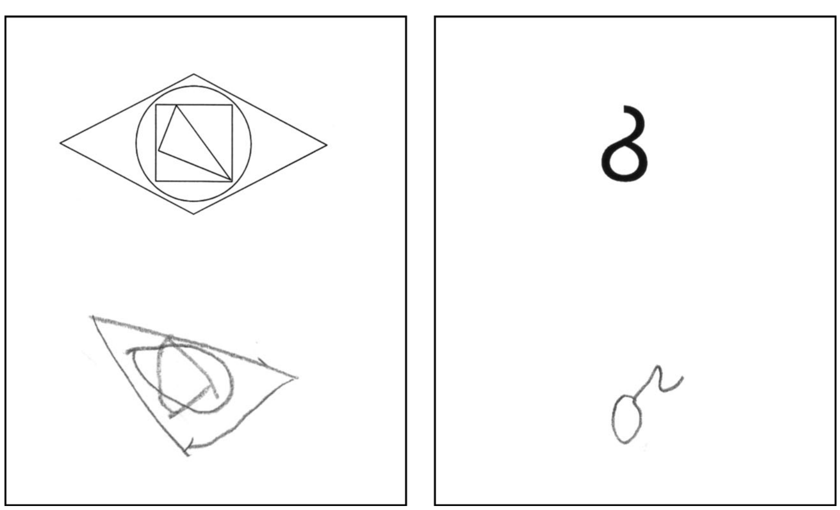

Figure 2. N.K.Y.'s copying performance. Model figures (top) and N.K.Y.'s copies (bottom).

This test requires understanding how the linguistic labels "left" and "right" apply to the corresponding sides of one's own or another's body. We next asked whether N.K.Y. nonetheless succeeds at differentiating left and right sides of stimuli, despite her inability to consistently label them appropriately. In a computerized task she used the left and right arrow keys to indicate whether a circular stimulus had its left or right side coloured. Stimuli were presented in various locations on the screen (left, right, top, or bottom), requiring N.K.Y. to separate the task-relevant left–right information (which side of the circle was coloured) from the task-irrelevant position of the stimulus on the screen. She was 99% correct (253/256), and, importantly, she responded accurately even when the left–right position of the stimulus as a whole conflicted with the correct response (e.g., the circle was positioned on the left side of the screen, but had its right side coloured). These results suggest that despite her difficulty with the terms "left" and "right", N.K.Y. is able to discriminate left from right, and at least under some circumstances can respond to relevant left–right information while ignoring irrelevant information.

Experimental studies

In the following experiments, we investigated N.K.Y.'s ability to perform spatial mapping tasks. As illustrated in Figure 1, these tasks required her to map left–right information from a source stimulus to a target stimulus, while ignoring the source's left–right position relative to the target.

Experiments 1a and 1b: Object-to-object mapping

In Experiments 1a and 1b N.K.Y. performed spatial mapping tasks with inanimate objects as source and target stimuli. In Experiment 1a the stimuli were paper rectangles taped to a whiteboard in front of N.K.Y., as in Figure 1. In Experiment 1b, illustrated in Figure 3, the stimuli were chairs, placed on the floor in front of N.K.Y. and separated by approximately the same distances as were the paper rectangles. All other aspects of the design and procedure were the same for Experiments 1a and 1b.

In both experiments source stimuli were positioned to the left and right of a centrally located target stimulus, all of which were placed in front of N.K.Y. at a distance of approximately 6 feet. For clarity the figures show only a single source stimulus, to the left of the target, although in all experiments both left and right source stimuli were present on all trials. On each trial a stimulus marker was placed on one of the two source stimuli, with the other source playing no role in the trial.

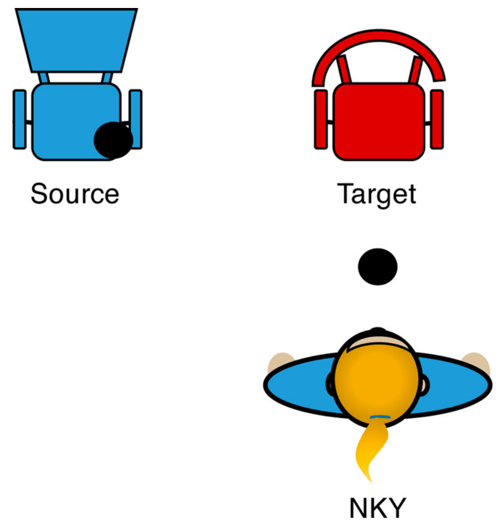

Figure 3. Object-to-object mapping (Experiment 1b). For clarity the figures show only a single source stimulus, to the left of the target. However, source stimuli were present on both the left and the right side of the target throughout the experiment. On each trial the marker was placed on only one of the two source stimuli. The other source played no role in the trial. [To view this figure in colour, please see the online version of this Journal.]

At the start of each trial N.K.Y. positioned a blindfold over her eyes, and the experimenter placed a marker object (a small magnetized plastic shape) on the left or right side of a source stimulus. In half of the trials the marker was placed on the source located to the left of the target, and in the other half the marker was placed on the right-side source. The position of the stimulus marker was counterbalanced so that it was placed on the left and right sides of the source equally often for source stimuli to the left and right of the target. After the marker was in position, N.K.Y. removed the blindfold, and responded by placing the response marker on the matching side of the target. For example, in the Experiment 1b trial shown in Figure 3, the stimulus marker was on the right side of the source chair, so the correct response was to place the response marker on the right side of the target chair. N.K.Y. was given an unlimited amount of time to respond, though she almost always responded promptly. Across two testing sessions, she completed 32 trials of the task with rectangle stimuli (Experiment 1a) and 64 trials with chairs (Experiment 1b).

In both experiments, N.K.Y. was 100% correct (96/96 overall). These results suggest that she is able to succeed in mapping the left–right position of the stimulus marker on the source to the corresponding side of the target, while ignoring potentially interfering information about the position of the source as a whole relative to the target.

Experiment 2: Person-to-person mapping

Experiment 2 was identical to Experiments 1a and 1b except that the source and target stimuli were people instead of objects, as shown in Figure 4 (the distinction in the figure between congruent and incongruent trials is explained below). On each trial, a stimulus marker was placed in a source model's left or right hand (always visible from N.K.Y.'s vantage point), and N.K.Y. responded by placing a response marker in the corresponding hand of the target model. Models always faced forward, so that N.K.Y. viewed them from behind.[1] Across four testing sessions, 128 trials were administered.

N.K.Y.'s performance was markedly different from that in Experiment 1. Although she was 81% correct overall (104/128), her performance depended critically on whether the position of the stimulus marker relative to the source was *congruent* or *incongruent* with the position of the source relative to the target. On *congruent* trials (Figure 4A), the left–right position of the source relative to the target (e.g., source to left of target) was the same as the left–right position of the marker relative to the source (e.g., marker on left side of source). On *incongruent* trials (Figure 4B) the position of the source relative to the target mismatched the position of the marker relative to the source (e.g., source model on the left, but stimulus marker in the source's right hand).

N.K.Y. was 100% correct on congruent trials, but only 63% correct (40/64) on incongruent trials, $\chi^2(1, N = 128) = 29.53$, $p < .001$. This incongruency effect suggests that the source model's position relative to the target model caused interference as N.K.Y. attempted to respond on the basis of the stimulus marker's position relative to the source. For instance, when the source was to the left of the target, holding an object in the right hand (as in Figure 4B), N.K.Y. often mistakenly put the response marker in the target's left hand.

N.K.Y.'s difficulty with this task is puzzling. The results from Experiments 1a and 1b indicate that she understands the task instructions and is not generally unable to ignore the position of source stimuli. Experiments 1a and 1b were structurally identical to Experiment 2, with the same instructions and the same requirement to ignore the position of the source stimuli; yet in those experiments N.K.Y. was 100% correct.

The observed dissociation between the object-to-object and person-to-person mapping tasks raises

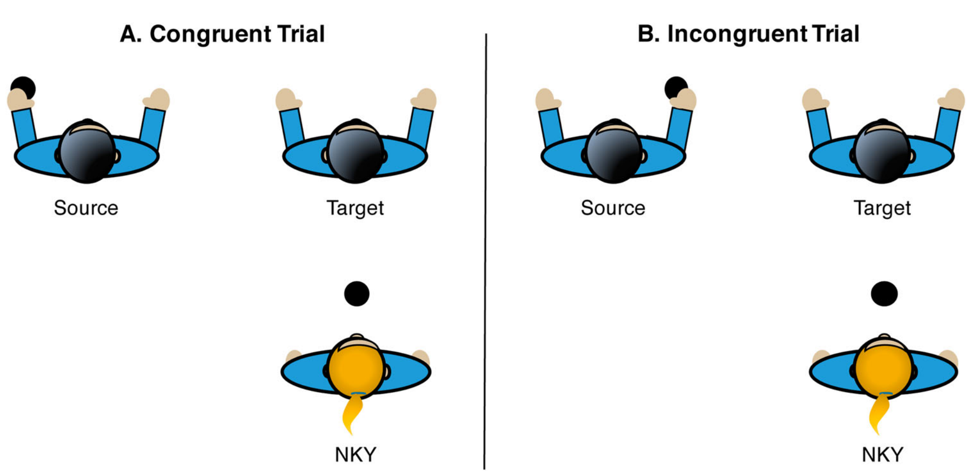

Figure 4. Person-to-person mapping (Experiment 2). (A) A congruent trial: The position of the source relative to the target (left) matches the location of the marker within the source (left). (B) An incongruent trial: The position of the source relative to the target (left) and the location of the marker (right) do not match. [To view this figure in colour, please see the online version of this Journal.]

the possibility that N.K.Y.'s performance reflects a simple difference between objects and people: Perhaps, for some unknown reason, she succeeds at spatial mapping tasks with objects yet fails with people. However, the next experiment argues against this possibility, showing that under some circumstances N.K.Y.'s performance is impaired even when the stimuli are objects.

Experiment 3: Modified object-to-object mapping

The experimental task was a simple variant of Experiment 1b (object-to-object mapping with chair stimuli). Specifically, the source chairs were placed not in front of N.K.Y. as in Experiment 1b, but rather to her immediate left and right (see Figure 5). All other aspects of the task remained the same.

N.K.Y. was 100% correct for congruent trials, but only 56% correct (9/16) for incongruent trials, $\chi^2(1, N = 32) = 8.96, p < .01$. Her performance on incongruent trials was significantly worse than her perfect performance in Experiment 1b (illustrated in Figure 3), $\chi^2(1, N = 48) = 16.39, p < .001$.

What is it about this modification that led to N.K.Y.'s errors? One possibility is that placing the source stimuli to her immediate left and right made the task more difficult because she could not see both the source and target at the same time. However, additional testing suggested that simultaneous visibility of source and target was not a significant factor.[2]

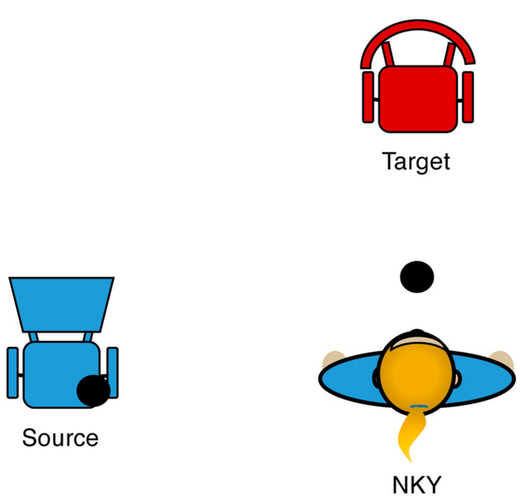

Figure 5. Modified object-to-object mapping (Experiment 3). The source is placed immediately to the left or right of N.K.Y. [To view this figure in colour, please see the online version of this Journal.]

The fundamental problem N.K.Y. faces in the spatial mapping task is one of relating reference frames (McCloskey, 2001). N.K.Y. must map positions in a source-based reference frame (e.g., "left" or "right" on the source) to positions in a target-based reference frame ("left" or "right" on the target). We suggest that different variants of the task prompt N.K.Y. to use different spatial mapping processes—and one of these processes leads her to errors, whereas the other does not. Specifically, we propose that in the original object-to-object mapping tasks (Experiments 1a and 1b) N.K.Y. set up a direct mapping between the source and target stimuli. In contrast, we suggest that in the present experiment she relied upon an indirect mapping process in which she mapped from the source to herself, and then from herself to the target. The difference in performance between Experiment 1a/1b (intact) and Experiment 3 (impaired) arose, we argue, because N.K.Y. is able to perform direct mapping accurately, but is impaired at indirect mapping.

Figure 6 illustrates the hypothesized direct and indirect mapping processes in the context of the spatial mapping tasks. In the direct mapping process (Figure 6A), N.K.Y. establishes direct correspondences between the sides of the source and the sides of the target, with the left side of the source corresponding to the left side of the target, and the right side of the source to the right side of the target (see Logan & Sadler, 1996, for a similar proposal in the context of other tasks). If, for example, the stimulus marker is placed on the source's left side, the direct correspondence *left side of source to left side of target* specifies that the response marker should be placed on the target's left side (Figure 6A).[3]

In the posited indirect mapping process (Figure 6B), N.K.Y. establishes a mapping between source and target with her own body as an intermediary (see Filimon, 2015, for a related suggestion). Specifically, she establishes a mapping between the source and herself, and then between herself and the target. For example, if the marker were placed on the source's left side, N.K.Y. would—if she performed the mapping process correctly—first map the source's left to her own left, and then map her left to the target's left.

In Experiment 1 the source stimuli were well in front of N.K.Y., and immediately to the left and right of the target stimulus (as in Figure 6A). Under these

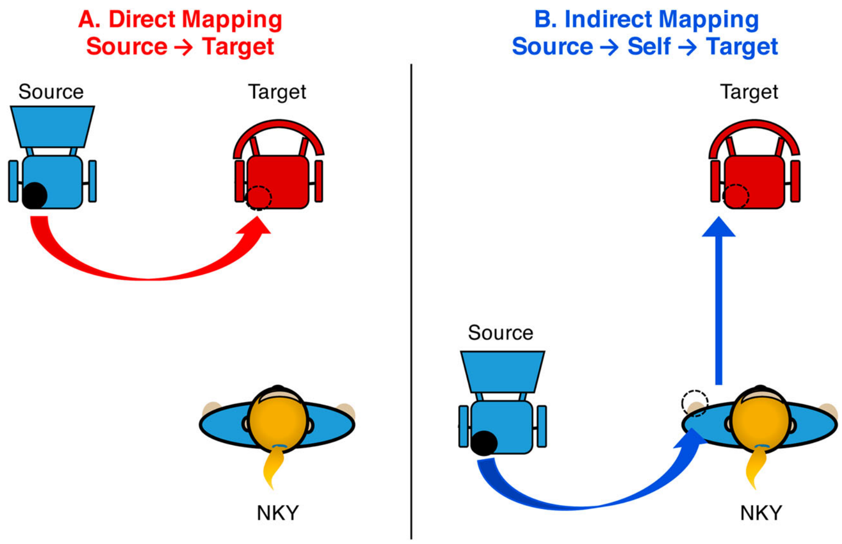

Figure 6. Direct and indirect mapping. (A) When the source is immediately next to the target, as in Experiment 1 (the object-to-object mapping task), N.K.Y. may have mapped the source directly to the target. (B) Moving the source from the immediate left or right of the target, to N.K.Y.'s immediate left or right, may have changed the mapping process, prompting N.K.Y. to relate the source first to her own body, then on to the target. [To view this figure in colour, please see the online version of this Journal.]

conditions the spatial relationship between source and target stimuli may have been most salient, leading N.K.Y. to establish direct source-to-target mappings. In Experiment 3, however, the source stimuli were immediately to N.K.Y.'s left and right, and well behind the target stimulus (see Figure 6B). Under these conditions the relationship of the sources to N.K.Y.'s own body may have been most salient: Previous research (Shusterman & Li, 2016) suggests that the positions to one's immediate left and right are especially salient and are strongly associated with left and right spatial concepts. The placement of sources to N.K.Y.'s immediate left and right may therefore have led her to perform the task by relating the source to herself, and then relating herself to the target: an indirect mapping process.

The same highly salient source position information that led her to use an indirect mapping, however, may also have led to errors via enhanced interference effects. Specifically, the source-to-self mapping process involves representing the marker position in an egocentric reference frame—for example, N.K.Y. maps the source's left or right to her own left or right side. However, the source's highly salient relationship to herself—that is, its position to her own left or right—is also salient left–right information that is represented in an egocentric reference frame. N.K.Y. is therefore faced with representing marker location in an egocentric reference frame, in the presence of highly salient egocentric information about the source's position. If that source position information is in conflict with the representation of marker location, interference is especially likely.

N.K.Y.'s difficulty in Experiment 3 (where she is likely to use an indirect mapping process), but not in Experiment 1 (where a direct mapping process is more likely) may therefore arise from the process of relating the source to herself, a critical subcomponent of the indirect mapping process. Specifically, in attempting to map the marked side of the source to her own body via an indirect mapping process, she has difficulty ignoring the source's irrelevant relationship to her body. For example, Figure 7 depicts an incongruent trial in which the source is on N.K.Y.'s left but the marker is on the source's right side. Under these conditions N.K.Y. has difficulty, we suggest, ignoring the spatial relationship of the source to herself (left) while attempting to map the marked side of the source (right) to a side of her body. Hence, she may erroneously map the right side of the source to the left side of her body. Then, when she (accurately) maps the left side of her body to the left side of the target, the result is an incorrect response.

To more directly assess whether N.K.Y. is impaired in source-to-self mapping when the location of the source could potentially create interference, we designed a new experiment that required N.K.Y. to relate the source to herself. In this *person-to-self*

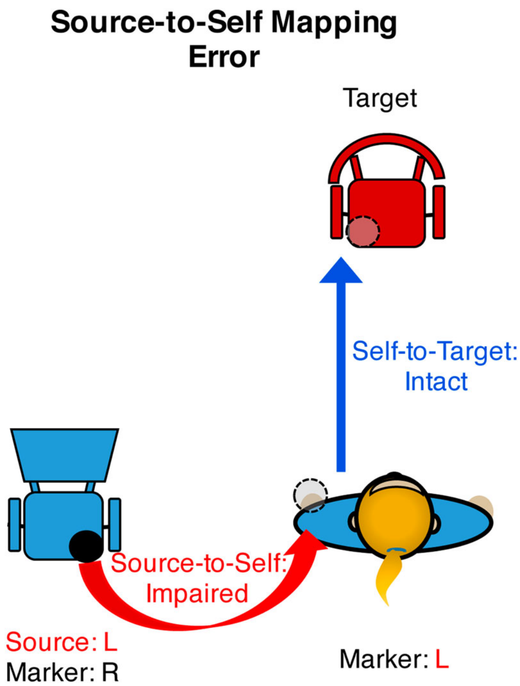

Figure 7. Source-to-self mapping error: When N.K.Y. maps from the source to her own body, its position relative to her body (left) interferes with her representation of the marker location (right), leading to an error. [To view this figure in colour, please see the online version of this Journal.]

mapping experiment, N.K.Y. herself was the target: After viewing a source model holding a stimulus marker in the left or right hand, N.K.Y. responded by placing the response marker in her own corresponding hand. This task requires N.K.Y. to relate the source to her body, and so we predicted that she would show impaired performance on the incongruent trials.

Experiment 4: Person-to-self mapping

In this experiment, two human source models stood beside N.K.Y., one to her immediate left and one to her immediate right. On each trial, the experimenter placed a stimulus marker in the left or right hand of either the left source or the right source. N.K.Y. then attempted to make herself match that source model, by placing the response marker in her own left or right hand. Figure 8 illustrates an incongruent trial: The source is to the left of the target (N.K.Y.'s body), but is holding the stimulus marker in his right hand. To respond correctly, N.K.Y. must map the right side of the source to her own right side, ignoring the fact that the source is positioned to her left. We predicted, however, that she would be unable to ignore the

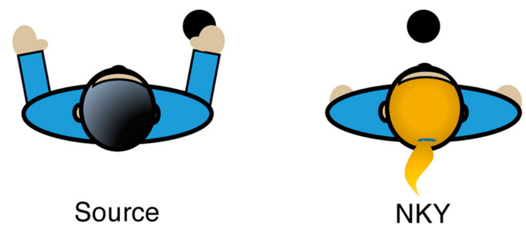

Figure 8. Person-to-self mapping (Experiment 4). [To view this figure in colour, please see the online version of this Journal.]

position of the source, and so would perform poorly on incongruent trials. N.K.Y. performed 96 trials of this task, 48 congruent and 48 incongruent. Counter-balancing of source position and marker placement was the same as that in previous experiments.

N.K.Y. was near-perfect (98% correct, 1 error) for the congruent trials, but only 31% correct (15/48) on incongruent trials, $\chi^2(1, N = 96) = 46.63$, $p < .001$. Her performance on incongruent trials was significantly below 50% correct ($p = .013$, binomial test), indicating that she responded more often on the basis of the (task-irrelevant) position of the source model relative to herself than on the basis of the (relevant) position of the stimulus marker relative to the source.

Preliminary conclusions: N.K.Y.'s deficit with mapping to her own body

N.K.Y.'s performance in Experiments 1a and 1b (the object-to-object mapping tasks) and Experiment 2 (the person-to-person mapping task) demonstrated a dissociation between seemingly minor variants of a spatial mapping task. In the latter experiment, N.K.Y. evidenced a strong incongruency effect, in which the source's position interfered with her response. Experiments 3 and 4 were designed to better understand the cause of this incongruency effect. Experiment 3 ruled out the interpretation that N.K.Y. simply performs well with objects and poorly with people, by demonstrating an incongruency effect in a task with objects as sources and targets. We suggested instead that in Experiment 3 N.K.Y. used an indirect source–target mapping process in which she mapped from the source to herself, and then from herself to the target. According to this interpretation, N.K.Y. is impaired in source-to-self mapping, and specifically has difficulty ignoring irrelevant information concerning the relationship of the source as a whole to herself. The interpretation was supported by Experiment 4 (the person-to-self mapping task), which showed severely impaired performance in a task that required N.K.Y. to map to her own body from source stimuli located to her immediate left or right.

Our interpretation raises an interesting possibility concerning N.K.Y.'s puzzling impairment in Experiment 2, the person-to-person mapping experiment (see Figure 4): Perhaps N.K.Y. performed poorly on the person-to-person mapping task because she used a source-to-self mapping process. This hypothesis would provide a parsimonious account of N.K.Y.'s impaired performance across tasks, by attributing her errors to a single impaired process (i.e., source-to-self mapping).

However, it is not immediately obvious why N.K.Y. would map from the source to her own body in Experiment 2. The task in this experiment did not fulfil the condition of having a salient relationship between N.K.Y.'s own body and the source: The source was positioned in front of her, not to her immediate left and right (see Figure 4). The tendency to map to her own body therefore cannot be explained by the same factors as those cited in Experiment 3 (the modified object-to-object mapping task). Also, the object-to-object mapping tasks in Experiments 1a and 1b did not show impairment, suggesting that these tasks—which were structurally identical to the person-to-person mapping task—did not elicit a source-to-self mapping process.

Our proposed resolution to this conundrum builds on the literature from spatial perspective taking. When reasoning about spatial information in contexts that include another person, participants have been found to spontaneously adopt the other's spatial perspective (Amorim, 2003; Mainwaring, Tversky, Ohgishi, & Schiano, 2003; Schober, 1993, 1995; Surtees, Noordzij, & Apperly, 2012; Tarampi, Heydari, & Hegarty, 2016). For instance, Tversky and Hard (2009) found that participants spontaneously described the location of an object as "to the left" when this description fitted the perspective of another person in the scene, even though it was in fact to their own right.

Spatial perspective taking is often described as a process of "putting ourselves into the shoes of another" (Surtees, Apperly, & Samson, 2013, p. 426) or representing ourselves in another's place (Franz, Ford, & Werner, 2007). We propose that N.K.Y. may be engaging in spatial perspective taking in the person-to-person mapping task—specifically, she may be adopting the perspective of the target, representing her own body as if it were in the target's place (Figure 9).

Representing herself in the target's place in the Person-to-Person mapping task would have two consequences. First, the process of mapping from source to target would become a process of (implicitly) mapping to her own body, as she is representing her body in the target's place. As a result, N.K.Y. may then be prone to making the same errors as those she makes in other instances that involve mapping to her own body. Second, in the person-to-person mapping task, although the sources were not positioned to N.K.Y.'s immediate left and right, they were positioned to the immediate left and right of the target. As discussed above, the position to one's immediate left and right are highly salient and are especially strongly associated with left and right (Shusterman & Li, 2016). If N.K.Y. imagined herself in the target's place in the person-to-person mapping task, she would presumably imagine the sources as being to her immediate left and right. As a result, N.K.Y. may have great difficulty ignoring the source's left–right position. On this account, the incongruency effect observed in the person-to-person mapping task would arise because in that task, like other cases where she has shown an incongruency effect,

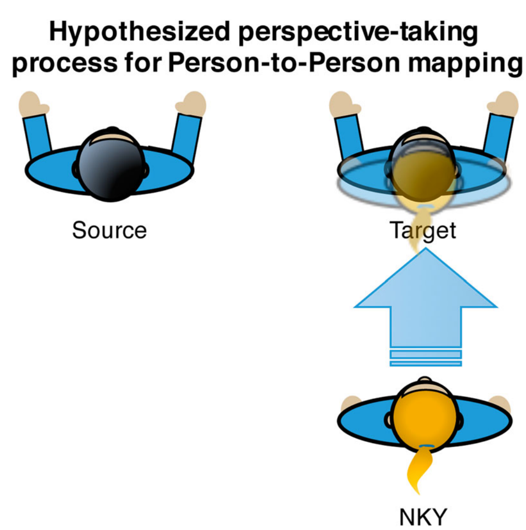

Figure 9. Proposed perspective-taking hypothesis. In person-to-person mapping, N.K.Y. adopts the spatial perspective of the target. In mapping the source to the target, she effectively maps the source to her own body, leading to errors due to her impaired source-to-self mapping abilities. [To view this figure in colour, please see the online version of this Journal.]

N.K.Y. is mapping left–right information to her own body in the presence of salient interfering position information—although in this case, she is representing her body as if it were in the target's place.

Figure 10 summarizes the proposed interpretation. In Experiment 1 (top row), the source is an object that is not in a salient relationship with N.K.Y. Under such conditions, N.K.Y. uses direct mapping and performs well. In Experiment 3 (second row), the source is an object that is now in a salient relationship with N.K.Y. The salient relationship to her body prompts an indirect mapping process, leading to poor performance due to her impaired source-to-self mapping. In Experiment 4 (third row) N.K.Y. is the target, so the task requires a source-to-self mapping, leading to the expected poor performance. Finally, in Experiment 2 (bottom row), the source is a person, but unlike in Experiment 4, another person (not N.K.Y.) is the target. Under such circumstances, we propose that N.K.Y. adopts the target's perspective and, in so doing, puts herself in a salient virtual relationship with the source, on which the source is to her immediate left or right. As a result, she maps to her own body, leading to poor performance.

This perspective-taking hypothesis makes an interesting prediction, which we test in the next experiment.

Experiment 5: Person-to-person mapping—source in middle

In this experiment, we returned to a variant of the spatial mapping task in which N.K.Y. was not the target. As in the person-to-person mapping task of Experiment 2, N.K.Y. was required to map from a human source model to a human target model. However, we modified the design of Experiment 2 by placing the source between N.K.Y. and the target (Figure 11). This modification ensures that the position of the source relative to N.K.Y. is always the opposite of its position relative to the target. For instance, if the source is on N.K.Y.'s left, it will be on the target's right. To ensure that N.K.Y. did not have to change her position during the task (and thereby change the position of the source relative to herself), we used a modified reporting procedure, illustrated in Figure 11. The target wore blue and red wristbands on his left and right hands, respectively. On each trial, the source raised either his left or right hand, and N.K.Y. responded by reporting the colour of the hand the target should raise to match the source. In the trial depicted in Figure 11, for example, the correct response would be "red hand".

Positioning the source between N.K.Y. and the target allows us to test a key prediction of the

Experiment	Relevant Task Properties	NKY's Performance	Interpretation
Expt. 1: Object-to-Object	Stimuli: Objects Source: In front of NKY	Good	Non-salient source-NKY relationship & salient source-target relationship ⇩ Direct source-to-target mapping (intact)
Expt. 3: Mod. Object-to-Object	Stimuli: Objects Source: Beside NKY	Poor	Salient source-NKY relationship ⇩ Indirect source-to-self-to-target mapping (source-to-self step impaired)
Expt. 4: Person-to-Self	Stimuli: People Source: Beside NKY	Poor	Salient source-NKY relationship & task requirements ⇩ Source-to-self mapping (impaired)
Expt. 2: Person-to-Person	Stimuli: People Source: In front of NKY	Poor	NKY adopts target perspective ⇩ Salient virtual source-NKY relationship ⇩ Indirect source-to-self-to-target mapping (source-to-self step impaired)

Figure 10. Summary of experiments, results, and proposed interpretations. A schematic of the experimental design (leftmost column), the relevant task properties (second from left), N.K.Y.'s performance (second from right), and the proposed interpretation of N.K.Y.'s performance (rightmost column). Experiments are presented in 1, 3, 4, 2 order. [To view this figure in colour, please see the online version of this Journal.]

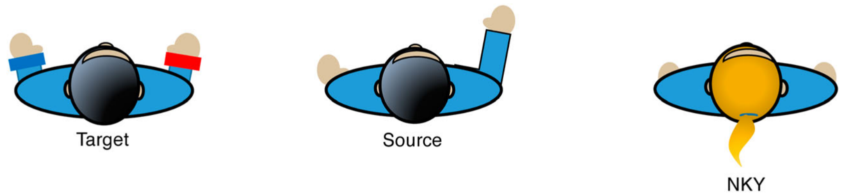

Figure 11. Person-to-person mapping—source in middle (Experiment 5). The source and target were positioned to one side of N.K.Y. The figure shows the arrangement of the task for one half of the trials; on the other half, the arrangement was mirrored so that both the source and the target were positioned to N.K.Y.'s right side. [To view this figure in colour, please see the online version of this Journal.]

perspective-taking hypothesis. Consider, for example, the case in which the source is positioned to N.K.Y.'s left, as illustrated in Figure 11. If N.K.Y. represents the position of the source relative to her actual position, she will represent source position as LEFT. If she then maps the stimulus location (e.g., right side of source) from the source to her own body, we would expect the LEFT source position representation to interfere on trials that require a "right" response. More generally, the interfering information should be the position of the source *relative to N.K.Y.'s actual position*.

However, if N.K.Y. adopts the target's perspective, she may represent the source's position as if she were in the target's place. That is, if the source is positioned to the *target's* right (as in Figure 11), N.K.Y. should represent its position as RIGHT, and show interference on trials that require a "left" response, even if the source is in fact to her left. More generally, the interfering information should be the position of the source *relative to the target*. Critically, the current experiment was designed to pit the representation of source position relative to N.K.Y. against its position relative to the target. The perspective-taking hypothesis makes the strong prediction that N.K.Y. should represent the source's position as if she were in the target's place.

The contrasting predictions may be summarized by considering once again the trial depicted in Figure 11. The source is raising his right hand and, relative to N.K.Y., is positioned to the left. Relative to N.K.Y.'s actual position, this is an incongruent trial. If N.K.Y. represents the position of the source relative to her actual position, then the trial should elicit poor performance. However, this same trial is congruent from the target's perspective—relative to the target, the source is positioned to the right, raising his right hand. If N.K.Y. adopts the perspective of the target—that is, if she imagines herself in the target's position—then she should perform well on this trial.

We classified trials based on the perspective from which they would be congruent: "Target-congruent" trials are those that are congruent from the target's perspective (and incongruent from N.K.Y.'s perspective), and "N.K.Y.-congruent" trials are trials that are congruent from N.K.Y.'s perspective (and incongruent from the target's perspective). If N.K.Y. represents the source's position relative to her actual position, we expect good performance in N.K.Y.-congruent trials and poor performance in target-congruent trials. If instead she adopts the perspective of the target, we expect good performance on target-congruent trials and poor performance on N.K.Y.-congruent trials.

N.K.Y. performed 24 trials of this task: 12 target-congruent and 12 N.K.Y.-congruent. On half of the trials both source and target were to N.K.Y.'s left, and on half both were to her right. Congruent status and position were counterbalanced across trials.

N.K.Y. was 100% correct in the target-congruent trials, but showed severe difficulty in the N.K.Y.-congruent trials, performing at only 8% correct (1/12), $\chi^2(1,\ N = 24) = 20.31$, $p < .001$. In short, N.K.Y. performed well when the trial was congruent from the perspective of the target, but very poorly when it was incongruent from that perspective (even though it was congruent from her actual spatial perspective).

These results provide strong evidence that N.K.Y. adopted the target's perspective. As expected, she showed an incongruency effect, whereby the source's left–right position interfered with her left–right response in the task. Critically, however, the source's position was represented *as if* N.K.Y. were in the target's place. Even when the source was on her left, for instance, her errors reveal that she represented its position as to the right—as it would be if she were adopting the target's perspective.

Explaining the dissociation

Taken together, these results support the interpretation proposed above of the dissociation between Experiments 1a and 1b (object-to-object mapping) and Experiment 2 (person-to-person mapping). On this interpretation, summarized in Figure 12, N.K.Y. is able to succeed at spatial mapping tasks when she maps directly from the source to the target (Figure 12A). However, when the task requires mapping to her own body (i.e., in a person-to-self mapping task), the source's left–right position interferes with her response, producing an incongruency effect (Figure 12B). Finally, for person-to-person mapping tasks in which N.K.Y. is not herself the target, she adopts the perspective of the target, and in so doing, represents the process of mapping from the source to the target as a process of mapping from the source to her own body (Figure 12C). As a result, the same difficulty with mapping to her own body leads to poor performance in person-to-person mapping tasks (Figure 12C). In sum, even though the object-to-object (Figure 12A) and person-to-person (Figure 12C) mapping tasks are structurally identical, N.K.Y. implicitly maps to her own body in the latter but not the former, producing the observed dissociation between them.

General discussion

In this article we investigated participant N.K.Y.'s performance in a series of spatial mapping tasks. These tasks required mapping left–right spatial information from a source stimulus to a target stimulus. We started with a puzzling dissociation: N.K.Y. performed perfectly in versions of a spatial mapping task using objects as source and target stimuli, but showed a pronounced incongruency effect in the same task when the objects were replaced by people. The subsequent experiments led to an interpretation of this dissociation, on which N.K.Y.'s performance results from both a deficit in mapping to her own body and a tendency to adopt the perspective of other people. In the following sections, we discuss some questions raised by our interpretation as well as their implications for understanding the computations involved in spatial perspective taking.

The spatial mapping task and N.K.Y.'s errors

Although to our knowledge no other developmental studies have utilized our specific spatial mapping tasks, many well-studied phenomena involve highly similar spatial mappings and can provide useful conceptual distinctions. For instance, research on the acquisition of the concepts of "left" and "right" suggests that knowledge of left and right requires establishing a spatial mapping from one's own left and right sides to those of others. Shusterman and Li (2016) describe the acquisition of left and right concepts as the process of solving three conceptually distinct problems. After learning to label their own left and right sides, children as early as 5 years of age begin to solve the problem of *extension*—that is, understanding left and right not only as labels for the different sides of their body, but also as directions extending from their body to define regions of space

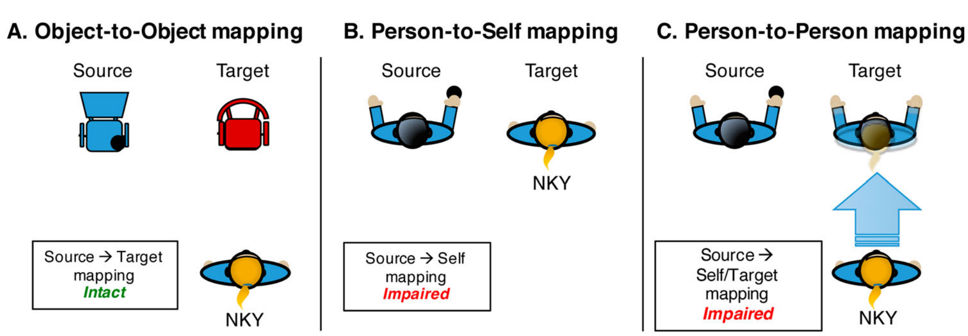

Figure 12. Proposed interpretation of dissociation between object-to-object mapping and person-to-person mapping. (A) In object-to-object mapping, N.K.Y. performs the task without difficulty, as she does not relate the source to her own body. (B) In person-to-self mapping, she is required to relate the source to her own body. In so doing the source's position overwhelms her response, leading to errors in incongruent trails. (C) In person-to-person mapping, N.K.Y. adopts the spatial perspective of the target. In mapping the source to the target, she effectively maps the source to her own body, leading to errors via the same processes as those in (B). [To view this figure in colour, please see the online version of this Journal.]

to the sides of their body (i.e., "the cup in my left hand" versus "the cup is to my left"). At around the same age, they also begin to solve the problem of *translation,* translating left–right vectors centred on one reference point to another reference point, as for instance might be required in discussing the left and right of someone else facing the same direction as you. Only much later, at approximately the age of 9, do children solve the problem of *rotation*, learning how to reason about the left and right of others who are rotated relative to their body (Piaget, 1928; Rigal, 1994).

N.K.Y.'s errors can be described as arising at the translation stage. In all of our tasks, the sources and targets were merely translated from N.K.Y.'s egocentric reference frame, not rotated. In contrast, the bulk of research on errors in spatial mapping involves tasks that require solving the problem of rotation. For instance, Piaget and Inhelder's (1956) seminal Three Mountain task asks the child to identify what another observer, who is looking at the same mountain model as the child but from the opposite side, would be able to see. Seven-year-olds often made "egocentric errors", reporting that the other person will see objects that they themselves can see, even if the objects are occluded by a mountain from the other's point of view (Surtees & Apperly, 2012). Similarly, when children are asked to report the orientation of a card that a person sitting on the other side of the table would see, 3-year-olds incorrectly reported the orientation that they could see themselves (Flavell, Everett, Croft, & Flavell, 1981). Similar errors are observed in adults for a variety of more complex tasks that involve reporting on rotated views (Hegarty & Waller, 2004; Wraga, Creem, & Proffitt, 2000).

Our spatial mapping tasks were designed to probe N.K.Y.'s spatial mapping abilities under the simplest conditions, when translation but not rotation was required. N.K.Y.'s errors therefore provide a novel opportunity to gain insights into the cognitive processes implicated in spatial mappings between translated stimuli.

Why does mapping to her own body cause an incongruency effect in N.K.Y.?

One of our key results was that N.K.Y. shows interference from the source's position when mapping to her own body. Why does this process of mapping to her own body lead to interference? Above, we suggested that a critical part of the explanation may lie in the reference frames that N.K.Y. uses to represent the source's position in the spatial mapping task, as well as the salience of the relationship between the source and her own body. Here we return to this issue, expanding on the interpretation in light of our findings.

The spatial mapping task involves several different reference frames. N.K.Y. must first decide whether the marker is on the source's left or right side. This decision requires representing the position of the marker in a source-based reference frame, defining its left–right position in relation to the midline of the source.

If N.K.Y. is engaging in direct mapping (mapping directly from the source to the target), the next step is to decide whether to place the marker object on the left or right side of the target. To do this, she must use a target-based reference frame, defining left and right in relation to the midline of the target. As we have seen, N.K.Y. seems to have no difficulty with direct mapping: In experiments like the object-to-object mapping experiment that elicit mapping directly from the source to the target, she is 100% correct. If, on the other hand, N.K.Y. maps the location of the marker object from the source to her own body, she must compute the corresponding position of the marker object in an egocentric reference frame, specifying whether it is on her own left or right. As we have seen, it is when she maps to her own body that the source's position tends to interfere with her response.

The selective interference when N.K.Y. maps to her own body may be due to the enhanced conflict between an egocentric representation of source position and an egocentric representation of marker location. A common assumption in models of spatial compatibility is that interference is stronger between spatial information that is coded in the same reference frame than that in different reference frames (Hommel, 1993; Kornblum et al., 1990). That is, there is greater conflict between "left of my body" and "right of my body" (as both "left" and "right" are represented in an egocentric reference frame) than there is between "left of the target" and "right of my body" (as they are represented in different reference frames). This state of enhanced conflict is exactly the situation N.K.Y. is likely to be in when she maps to her own body. When N.K.Y. first locates the source to begin the process of mapping to her own body, she is relying on an egocentric representation of source position, representing the source as being to her left or right. Of course, the result of this mapping is also an egocentric representation: a representation of the location of the marker as being on her own left or right side. As a result, in cases when N.K.Y. maps to her own body, she generates two egocentric left–right representations, one for the source's position, and one for the location of the marker. When these two representations conflict (on incongruent trials), she is especially prone to interference.

We have argued that this same explanation underlies N.K.Y.'s errors when she adopts another's perspective. An interesting consequence of this interpretation is that by adopting another's perspective, N.K.Y. is apparently able to generate egocentric representations that are not centred on her actual body location. That is, when adopting the perspective of the target, N.K.Y. is representing the source's position as if he were to her own left—that is, using an egocentric representation—when in fact he is to her right, and vice versa. This result provides an interesting example, joining a collection of recently documented cases (Filimon, 2015), of the use of a putatively non-egocentric reference frame (a representation of source position relative to the target) that is, at root, an egocentric reference frame (a representation of source position *as if I were in the target's place*).

The representation of position in spatial perspective taking

Our results from N.K.Y. also shed light on the closely related issue of how observers represent their own position when adopting another's perspective. A critical assumption in work on perspective taking is that it involves representing oneself in another's position, as "put[ting] ourselves into the shoes of another" (Surtees et al., 2013, p. 426). Surprisingly, few studies have directly investigated how observers represent their position when adopting another's perspective. Directly investigating the observer's representation of their own position is important, as many of the results from putative perspective-taking tasks admit other explanations that do not involve mentally representing oneself in another's position. For instance, tasks that ask the observer what another person can see from their perspective may occasionally be solved by line-of-sight tracing (Michelon & Zacks, 2006), which does not require adopting another's position. Additionally, some results thought to critically involve aligning one's perspective with another's (and thereby representing oneself in their position) may be re-interpreted without assuming any such process. Several studies have shown that the time required to adopt another's perspective varies with angular deviation of the to-be-assumed perspective from the observer's own perspective—the so-called *angular disparity effect* (Graf, 1994; Keehner, Guerin, Miller, Turk, & Hegarty, 2006; Kozhevnikov & Hegarty, 2001; Michelon & Zacks, 2006). However, it has been suggested that the effect may be interpreted as resulting from sensorimotor interference (May, 2004). Specifically, the increasing deviation of the other's perspective from one's current head direction results in heightened conflict with one's own proprioceptive experience of head direction, causing greater sensorimotor interference and slower reaction times (although see Kessler & Thomson, 2010, for evidence challenging this claim).

It is also important to note that simply observing an interference effect, without identifying the reference frames involved, is insufficient to demonstrate that observers are necessarily representing themselves in another's position. For example, in a clever experiment designed to test whether the attribution of agency could elicit perspective taking, Zwickel (2009) used the Frith–Happé animations (Abell, Happé, & Frith, 2000; Heider & Simmel, 1944) involving triangles that move around the screen, with one appearing to "chase" the other. Participants judged whether a dot that randomly appeared on the screen was to the left or right of one of the triangles (with left and right judgments made relative to the observer's own perspective). In trials eliciting an agency attribution, participants were slower to make left–right judgments when the position of the dot relative to the triangle's perspective conflicted with the position relative to their own perspective. While this work provides strong evidence that the observer represented the triangle as *having* a perspective, it is not clear that the observer *adopted* that perspective in any sense that involves mentally assuming the triangle's position. Interference effects may arise from conflicting position representations in *different* reference frames (for a helpful taxonomy of many such cases, see Kornblum et al., 1990). Specifically, the observer may have represented the dot as positioned to *her own* left (in an egocentric reference frame) while representing it as positioned to *the triangle's* right (in a triangle-centred reference frame)—and this conflict between left and right in different reference frames could lead to the observed interference effect. To conclude that the observer actually adopted the triangle's perspective requires evidence that the conflict arose within an egocentric reference frame: that the dot was represented as both "to the left" of the observer and "to the right" of the observer, and what has changed is where the observer represents herself to be in the two instances.

N.K.Y.'s deficit, we argue, provides a reliable indicator of the positions she represents as to the left or right of her body, and thereby meet this criterion. As we have seen, N.K.Y.'s errors involve interference from the source's position when she maps left–right information to her own body. Given that her errors arise when mapping the source to her own body, the left–right value of the interfering position information reveals how she represents the position of the source in relation to her body—for example, if "left" information is interfering with her "right" responses, this indicates not only that (a) she is mapping to her own body—a precondition for making errors in the first place—but also that (b) she is representing the source as if it were to the left of her body. As discussed above, this occurs even in cases when, in fact, the source is *not* to the left of her own body (e.g., in Experiment 5, where the source might be presented on the right of N.K.Y., but her responses indicate that she represented its position as LEFT). We concluded from this finding that she represented her body in a different position: Although the source is in fact to her right, she represented her body in a position (specifically, in the position of the target) from which the source was to her left. In this sense, the interfering position information tells us how N.K.Y. represents the source's position in relation to her body and, by implication, where she represents her own body to be. These findings provide novel evidence suggesting that one form of spatial perspective taking involves updating a representation of one's bodily position as coinciding with that of the person whose perspective one is adopting.

While N.K.Y.'s deficit provided an important tool for drawing such conclusions, it is not impossible to use similar logic with neurotypical individuals. A recent article from Cavallo, Ansuini, Capozzi, Tversky, and Becchio (2017) provides converging evidence that perspective taking involves representing oneself in another's position, by capitalizing on the findings that (a) right-handers are quicker to make judgments about objects on their right (Furlanetto, Gallace, Ansuini, & Becchio, 2014; Olson & Laxar, 1973), and (b) people are faster to respond to stimuli that are closer to them, with reaction times increasing in proportion to distance from oneself (Sun & Wang, 2010). In the Cavallo et al. study, right-handed participants viewed a virtual table as if they were seated at one end of it. Objects were presented on their left or right side, either closer or further from them. At the other end of the table, a human avatar was presented facing the participant. Participants judged whether the object was presented on the left or on the right. On some trials participants were told to make the judgment from their own perspective, and on others they were told to make it from the avatar's perspective. As expected, when making self-perspective judgments participants were faster for objects on their own right, and when the object was closer to them. When making judgments from the avatar's perspective, however, they were fastest when the object was on the right of and closer to the avatar. These results suggest that observers "remapped" (Cavallo et al., 2017) the position of the object, as if *they* were in the avatar's position. Similar to our findings from N.K.Y., these findings support the conclusion that when adopting another's perspective, observers actively represent their own position as if it coincided with the other's, changing the way they represent the positions of surrounding stimuli.

Which stimulus properties trigger spatial perspective taking?

We have provided evidence that in spatial mapping tasks with people as sources and targets, N.K.Y. adopts the perspective of the target. N.K.Y.'s tendency to adopt the perspective of other people in these tasks is interesting because the spatial mapping task did not *require* perspective taking. Her good performance in the object-to-object mapping task shows this empirically, and highlights that perspective taking seems to have been triggered by people in a way that it is not by objects, a finding echoed by a large body of research (Amorim, 2003; Mainwaring et al., 2003;

Schober, 1993, 1995; Surtees et al., 2012; Tarampi et al., 2016).

However, the precise stimulus properties that trigger spatial perspective taking are still not well understood. Some authors have suggested that the mere attribution of agency is sufficient to elicit automatic perspective taking: Once an external stimulus is deemed an agent, we are predisposed to adopt its perspective (Zwickel, 2009). Alternatively, theories of imitation posit a common representational format for the bodies of self and other (Catmur, Walsh, & Heyes, 2009; Meltzoff & Moore, 1997) that potentially triggers automatic perspective taking. Other researchers highlight the phenomenon of motor resonance, emphasizing the importance not just of the similarity of form, but also of possibility for actions, for eliciting automatic perspective taking (Avenanti, Bolognini, Maravita, & Aglioti, 2007; Avenanti, Candidi, & Urgesi, 2013; Grèzes & Decety, 2001).

An additional experiment we performed with N.K.Y. may bear on this question. In this experiment, as in Experiments 1 and 2, the sources and targets were in front of N.K.Y. with sources to the left and right of the central target. However, in this task the source and target stimuli were paper cut-outs made from photos of humans. The cut-outs were approximately 8 inches tall and depicted real people, viewed from the rear, much like the view that N.K.Y. had of the human sources and targets in Experiment 2. N.K.Y. was 100% correct, contrasting with her impaired performance with real people and similar to that in the object-to-object mapping tasks. These results hint that the form of a person, per se, is not sufficient to elicit perspective taking, although we do not draw strong conclusions from these results due to the obvious differences in size and dimensionality between these paper cut-outs and real people. Exactly which stimulus properties lead to perspective taking remains an active area of research, but what is clear is that whatever property or properties those are, other humans possess them, whereas objects (at least those used in our studies) did not.

Conclusion

In this article we investigated participant N.K.Y.'s dissociation in performance between two versions of a spatial mapping task: one in which non-human objects were used as stimuli, and N.K.Y. performed perfectly, and one in which the objects were replaced by people, in which she was significantly impaired. In a series of follow-up experiments, we outlined an interpretation of this dissociation. We found that N.K.Y. tends to adopt the perspective of human targets, implicitly representing the process of mapping from the source to the target as involving mapping to her own body, a process for which N.K.Y. is impaired.

Our findings shed light on the nature of N.K.Y.'s specific deficit, as well as providing more general insight into the cognitive processes involved in performing the spatial mapping task and engaging in perspective taking. N.K.Y.'s dissociation provides a clear case in which seemingly identical tasks can nonetheless trigger very different cognitive processes. Neurotypical individuals are also found to engage in spontaneous perspective taking when performing spatial tasks with other people (Amorim, 2003; Mainwaring et al., 2003; Schober, 1993, 1995; Surtees et al., 2012; Tarampi et al., 2016). However, without the special difficulties in mapping to their own body resulting from N.K.Y.'s spatial deficit, differential processes used for objects and people may not lead to different performance, and thereby might easily go undetected. N.K.Y.'s deficit provides a clear demonstration that these processes are separable, and further highlights the value of studying atypical cognition to gain a deeper understanding of normal cognition.

Notes

1. This arrangement ensured that the intrinsic left and right sides of the source and target models were not in conflict with their left and right sides relative to N.K.Y., as would have been the case if the models were facing N.K.Y. For example, if the target model had faced N.K.Y., the target's right hand would have been on the left relative to N.K.Y., and the target's left hand would have been on the right.
2. In a second modification of the chairs mapping task, the chairs were in the same positions as in Experiment 1b (in front of N.K.Y., as in Figure 3) but she was prevented from viewing source and target chairs simultaneously. On each trial, the target chair was occluded by a blanket while N.K.Y. viewed the stimulus marker on the source chair. N.K.Y. then put on a blindfold, and the occluder was shifted from the target chair to the source chair, following which N.K.Y. removed the blindfold and made her response. She performed extremely well in this task, with no difference between congruent and incongruent trials

[100% and 91% (1 error), respectively, Fisher's exact test: $p = .5$], suggesting that the inability to see both source and target at the same time is not responsible for her poor performance in Experiment 3.

3. We do not assume that N.K.Y. necessarily uses the linguistic labels "left" and "right" in representing the sides of the sources and targets (or other stimuli). The representations distinguishing left and right may be non-linguistic spatial representations.

Acknowledgements

The authors thank Kristen Johannes and members of the Cognitive Neuroscience Lab at Johns Hopkins for their helpful comments on earlier drafts of this article. We are especially grateful to N.K.Y. and her mother for their patience and good humour throughout the study. It was a pleasure to collaborate with both of them.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported by funding from the Johns Hopkins Science of Learning Institute.

References

Abell, F., Happé, F., & Frith, U. (2000). Do triangles play tricks? Attribution of mental states to animated shapes in normal and abnormal development. *Cognitive Development*, *15*(1), 1–16. doi:10.1016/S0885-2014(00)00014-9

Amorim, M. A. (2003). "What is my avatar seeing?": The coordination of "out-of-body" and "embodied" perspectives for scene recognition across views. *Visual Cognition*, *10*(2), 157–199. doi:10.1080/713756678

Avenanti, A., Bolognini, N., Maravita, A., & Aglioti, S. M. (2007). Somatic and motor components of action simulation. *Current Biology*, *17*(24), 2129–2135. doi:10.1016/j.cub.2007.11.045

Avenanti, A., Candidi, M., & Urgesi, C. (2013). Vicarious motor activation during action perception: Beyond correlational evidence. *Frontiers in Human Neuroscience*, *7*. doi:10.3389/fnhum.2013.00185

Benton, A. L., Hamsher, N. R., & Spreen, O. (1983). *Contributions to neuropsychological assessment: A clinical manual*. New York, NY, USA: Oxford University Press.

Catmur, C., Walsh, V., & Heyes, C. (2009). Associative sequence learning: The role of experience in the development of imitation and the mirror system. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1528), 2369–2380. doi:10.1098/rstb.2009.0048

Cavallo, A., Ansuini, C., Capozzi, F., Tversky, B., & Becchio, C. (2017). When far becomes near: Perspective taking induces social remapping of spatial relations. *Psychological Science*, *28*(1), 69–79. doi:10.1177/0956797616672464

Filimon, F. (2015). Are all spatial reference frames egocentric? Reinterpreting evidence for allocentric, object-centred, or world-centred reference frames. *Frontiers in Human Neuroscience*, *9*, 941. doi:10.3389/fnhum.2015.00648

Flavell, J. H., Everett, B. A., Croft, K., & Flavell, E. R. (1981). Young children's knowledge about visual-perception—further evidence for the Level 1–Level 2 distinction. *Developmental Psychology*, *17*, 99–103. doi:10.1037/0012-1649.17.1.99

Franz, E. A., Ford, S., & Werner, S. (2007). Brain and cognitive processes of imitation in bimanual situations: Making inferences about mirror neuron systems. *Brain Research*, *1145*, 138–149. doi:10.1016/j.brainres.2007.01.136

Furlanetto, T., Gallace, A., Ansuini, C., & Becchio, C. (2014). Effects of arm crossing on spatial perspective-taking. *PLOS ONE*, *9*(4), e95748. doi:10.1371/journal.pone.0095748

Graf, R. (1994). *Self-rotation and spatial reference: The psychology of partner-centred localisations*. Frankfurt: Peter Lang.

Grèzes, J., & Decety, J. (2001). Functional anatomy of execution, mental simulation, observation, and verb generation of actions: A meta-analysis. *Human Brain Mapping*, *12*(1), 1–19. doi:10.1002/1097-0193(200101)12:1<1::AID-HBM10>3.0.CO;2-V

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence*, *32*, 175–191. doi:10.1016/j.intell.2003.12.001

Heider, F., & Simmel, M. (1944). An experimental study of apparent behavior. *The American Journal of Psychology*, *57*(2), 243–259. doi:10.2307/1416950

Hommel, B. (1993). Inverting the Simon effect by intention. *Psychological Research*, *55*(4), 270–279. doi:10.1007/BF00419687

Keehner, M., Guerin, S. A., Miller, M. B., Turk, D. J., & Hegarty, M. (2006). Modulation of neural activity by angle of rotation during imagined spatial transformations. *NeuroImage*, *33*(1), 391–398. doi:10.1016/j.neuroimage.2006.06.043

Kessler, K., & Thomson, L. A. (2010). The embodied nature of spatial perspective taking: Embodied transformation versus sensorimotor interference. *Cognition*, *114*(1), 72–88. doi:10.1016/j.cognition.2009.08.015

Kirkham, A. J., & Tipper, S. P. (2015). Spatial compatibility interference effects: A double dissociation between two measures. *Visual Cognition*, *23*(8), 1043–1060. doi:10.1080/13506285.2015.1110653

Klatzky, R. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. *Spatial Cognition*, *1404*, 1–17. doi:10.1007/3-540-69342-4_1

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility–a model and taxonomy. *Psychological Review*, *97*(2), 253–270. doi:10.1037/0033-295X.97.2.253

Kornblum, S., Stevens, G. T., Whipple, A., & Requin, J. (1999). The effects of irrelevant stimuli: 1. The time course of stimulus–stimulus and stimulus–response consistency effects with Stroop-like stimuli, Simon-like tasks, and their factorial combinations. *Journal of Experimental Psychology: Human*

Perception and Performance, *25*(3), 688–714. doi:10.1037/0096-1523.25.3.688

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition*, *29*(5), 745–756. doi:10.3758/BF03200477

Levinson, S. C. (1996). Frames of reference and Molyneux's question: Crosslinguistic evidence. In P. Bloom, M. A. Peterson, L. Nadel, & M. F. Garrett (Eds.), *Language and space* (pp. 109–169). Cambridge, MA: MIT Press.

Logan, G. D., & Sadler, D. D. (1996). A computational analysis of the apprehension of spatial relations. In *Language and space.* (pp. 493–529). Cambridge, MA, US: The MIT Press.

Mainwaring, S. D., Tversky, B., Ohgishi, M., & Schiano, D. J. (2003). Descriptions of simple spatial scenes in English and Japanese. *Spatial Cognition & Computation*, *3*(1), 3–42. doi:10.1207/S15427633SCC0301_2

May, M. (2004). Imaginal perspective switches in remembered environments: Transformation versus interference accounts. *Cognitive Psychology*, *48*(2), 163–206. doi:10.1016/S0010-0285(03)00127-0

McCloskey, M. (2001). Spatial representation in mind and brain. In B. Rapp (Ed.), *What deficits reveal about the human mind/brain: A handbook of cognitive neuropsychology* (pp. 101–132). Philadelphia: Psychology Press.

Meltzoff, A. N., & Moore, M. K. (1997). Explaining facial imitation: A theoretical model. *Early Development and Parenting*, *6*(3–4), 179–192. doi:10.1002/(SICI)1099-0917(199709/12)6:3/4<179::AID-EDP157>3.0.CO;2-R

Michelon, P., & Zacks, J. M. (2006). Two kinds of visual perspective taking. *Perception & Psychophysics*, *68*(2), 327–337. doi:10.3758/BF03193680

Olson, G. M., & Laxar, K. (1973). Asymmetries in processing the terms "right" and "left". *Journal of Experimental Psychology*, *100*(2), 284–290. doi:10.1037/h0035453

Piaget, J. (1928). *The child's conception of the world*. London, UK: Routledge and Kegan Paul Ltd. doi:10.4324/9781315006215

Piaget, J., & Inhelder, B. (1956). *The child's conception of space*. London: Routledge & Kegan Paul.

Rigal, R. (1994). Right-left orientation: Development of correct use of right and left terms. *Perceptual and Motor Skills*, *79*(3), 1–20. doi:10.2466/pms.1994.79.3.1259

Schober, M. F. (1993). Spatial perspective-taking in conversation. *Cognition*, *47*(1), 1–24. doi:10.1016/0010-0277(93)90060-9

Schober, M. F. (1995). Speakers, addressees, and frames of reference: Whose effort is minimised in conversations about locations? *Discourse Processes*, *20*(2), 219–247. doi:10.1080/01638539509544939

Shusterman, A., & Li, P. (2016). Frames of reference in spatial language acquisition. *Cognitive Psychology*, *88*, 115–161. doi:10.1016/j.cogpsych.2016.06.001

Sun, Y., & Wang, H. (2010). Perception of space by multiple intrinsic frames of reference. *PLOS ONE*, *5*(5), e10442. doi:10.1371/journal.pone.0010442

Surtees, A. D., & Apperly, I. A. (2012). Egocentrism and automatic perspective taking in children and adults. *Child Development*, *83*(2), 452–460. doi:10.1111/j.1467-8624.2011.01730.x

Surtees, A., Apperly, I., & Samson, D. (2013). Similarities and differences in visual and spatial perspective-taking processes. *Cognition*, *129*(2), 426–438. doi:10.1016/j.cognition.2013.06.008

Surtees, A. D. R., Noordzij, M. L., & Apperly, I. A. (2012). Sometimes losing your self in space: Children's and adults' spontaneous use of multiple spatial reference frames. *Developmental Psychology*, *48*(1), 185–191. doi:10.1037/a0025863

Tarampi, M. R., Heydari, N., & Hegarty, M. (2016). A tale of two types of perspective taking: Sex differences in spatial ability. *Psychological Science*, *27*(11), 1507–1516. doi:10.1177/0956797616667459

Torgesen, J. K., Rashotte, C. A., & Wagner, R. K. (1999). *Towre: Test of word reading efficiency*. Austin, TX: Pro-ed.

Tversky, B., & Hard, B. M. (2009). Embodied and disembodied cognition: Spatial perspective-taking. *Cognition*, *110*(1), 124–129. doi:10.1016/j.cognition.2008.10.008

Wraga, M., Creem, S. H., & Proffitt, D. R. (2000). Updating displays after imagined object and viewer rotations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(1), 151–168. doi:10.1037//0278-7393.26.1.151

Zwickel, J. (2009). Agency attribution and visuospatial perspective taking. *Psychonomic Bulletin & Review*, *16*(6), 1089–1093. doi:10.3758/PBR.16.6.1089