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Mental Paper Folding Revisited: The Involvement of Visual Action Imagery

Stephan Frederic Dahm [1,2,*] and Clemens Draxler [2]

[1] Department of Psychology, Faculty of Psychology and Sports Sciences, Universität Innsbruck, 6020 Innsbruck, Austria
[2] Department of Psychology and Sports Medicine, Institute of Psychology, UMIT TIROL—Private University of Health Sciences and Health Technology, 6060 Hall in Tyrol, Austria
* Correspondence: stephan.dahm@uibk.ac.at

Abstract: Action imagery describes a mental representation of an action and its consequences. Although it is widely recognized that people differ in their ability to imagine actions, objective validated tests to measure such differences are scarce. In search of an objective testing method for action imagery ability, the present study investigated whether solving mental paper-folding tasks involves action imagery. The stimuli were two-dimensional grids of six squares. A total of 99 participants mentally folded each grid into a three-dimensional cube to judge whether two highlighted lines in the grid overlapped in the imagined cube. This was done in two sessions of 214 judgements each, where the grids differed in overlaps, the least number of imagined folds, and the least number of imagined directional changes. Error rates and reaction times increased with the number of imagined folds and with the number of directional changes. Furthermore, more errors were committed with overlapping lines than with no overlaps. This was not reflected in the reaction times. Hence, the reaction times increased when the stepwise folding process was enlarged, but not when the final selection was more difficult. We concluded that the participants predominantly used action imagery as a task-solving strategy rather than for abstract problem-solving.

Keywords: motor imagery; action imagery ability; mental action representation

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1. Introduction

Action imagery (also called motor imagery) involves the mental representation of an action, without the actual execution of the action [1], and may also include the action's consequences [2,3]. It is assumed that action imagery shares common mechanisms with action execution for the prediction of the action's consequences [2,4,5]. Such functional equivalence has been supported by brain imaging studies showing an overlap in activated brain areas during action imagery and action execution [6]. Furthermore, behavioral studies have shown that imagination and execution durations are constrained by the same factors [7–9], and that the amount of action errors in both imagination and execution depends on motor expertise and familiarization with the action [2,10]. For instance, cognitive constraints such as the visual similarity of stimuli and instructional mapping influence the imagination durations and execution durations of bimanual responses in a similar fashion [8].

It is assumed that individuals differ in their abilities to imagine actions [11,12]. Action imagery ability predicts performance improvements after the repetitive use of action imagery [13], but it has often been assessed with questionnaires that rely on self-ratings [14]. Objective testing measures for action imagery ability are still scarce [14]. Therefore, the present study tested whether mental paper folding involves action imagery. For this aim, we tested whether task characteristics that would increase folding durations in actual execution would also increase reaction times (RTs) in the mental paper-folding task, thereby revealing the use of action imagery to solve the task [15]. For instance, the least number of folds not only influences the folding durations in execution, but also influences the durations of action imagery, increasing RTs in the mental folding task [15].

In 1972, Roger N. Shepard and Christine Feng [15] presented a study about the chronometry of mental paper folding, which involves the representation and transformation of mental images. In contrast to a very similar task—the mental rotation task by Shenna Shepard and Douglas Metzler [16]—the mental paper-folding task has attracted rather little further attention [17,18] or has been intertwined with other constructs, such as math skills or strategy creation [19,20]. In the mental rotation task, participants judge the matching between two objects that are shown from different angles in space. In the mental paper-folding task, a two-dimensional grid of squares is shown that can be folded in a three-dimensional manner. Participants may indicate whether two highlighted lines in the two-dimensional grid would overlap if the grid was folded [15]. The present study explores the mental paper-folding task to explain potential stimulus characteristics that influence reaction times (RTs) and error rates as well as learning effects after extensive use of the task.

It has been shown that mental paper folding involves the activation of brain areas associated with higher cognitive functions [21,22] and processing of spatial information about orientation and position [17,23], as well as perception and object recognition [24]. Most importantly, brain activation during mental paper folding has been associated with action imagery and motor simulation [25]. Apart from brain imaging studies, it has been shown that mental paper folding is associated with executive functioning, visuospatial working memory, and visuospatial short-term memory [26]. Furthermore, a behavioral study showed that synchronous execution of both cognitive and motor tasks interferes with the acquisition of origami folding [27]. In line with the assumption of functional equivalence between imagination and execution [5], visuomotor action imagery [28] is involved when planning the execution of paper folding [27] or following instructions to imagine paper folding [15].

To assess possible subdimensions of imagery ability, previous studies analyzed sets of various imagery tasks and questionnaires [29,30]. Low correlations between the tasks and the factor loadings indicated several subdimensions of imagery ability for tasks and questionnaires. However, separate factors might have evolved due to methodological differences (instead of theoretical dimensions) between tasks, e.g., accuracy, reaction time, and self-reports [29,31]. Apart from indicating subdimensions of imagery ability [30], low correlations between the tasks may also indicate that solving the tasks involves other abilities (e.g., geometric knowledge, working memory, reasoning, motor responses) in addition to imagery ability [14,26]. In any case, these studies [29,30]—as well as the mental rotation task [16]—mainly assessed visuospatial imagery ability, whereas the present study focuses on imagery ability that involves an action. In action imagery, four dimensions have been proposed [32] that are in line with Kosslyn's dimensions in general imagery [30]. First, image generation involves the creation of an imagined perception (which may be visual, auditory, etc.) using memorized representations. Second, image inspection involves focusing on details to interpret and extract information. Third, image transformation involves the intentional manipulation of the imagined content. In action imagery this includes the continuous process of the action itself. Fourth, image maintenance or controllability involves the ability to not fade out of the imagined perception.

In the present study, an outright sample of all possible stimuli for the mental paper-folding task [15,18] was created (https://osf.io/tj8h2) (accessed on 11 November 2022). We assumed that solving the mental paper-folding task implicitly requires the use of imagery [20], even when imagery is not explicitly instructed [33]. Response accuracy decreases with the number of relevant and distractor folds [20]. Furthermore, relevant folds predict accuracy better than distractor folds [20]. Empirical evidence has been obtained showing that, independent of item difficulties [20], RTs give additional information about the underlying strategies or abilities that individuals use to solve the task [31]. Assuming that action imagination follows the rules of human actions in a stepwise manner, it is expected that RTs will increase when the number of relevant folds increases [15,18]. Additionally, to extend previous findings, it is expected that RTs will increase when the number of directional changes during folding increases, because either the imagined hand position or the imagined position of the sheet of paper needs to be turned. Alternatively, mental object transformation based on technical rules may involve simultaneous folding of all sheets at once. Furthermore, decisions about overlaps could also be solved with tacit knowledge or abstract problem-solving strategies [34], e.g., a heuristic rule could be that two lines match if they are set opposed to one another with three squares in between. It has been shown that heuristic rules are (sometimes) used in mental paper folding when analyzing accuracy [20]. In the present study, RTs were not expected to depend on the number of relevant folds and directional changes using such abstract problem-solving strategies [34].

It has been shown that familiarity with mental rotations or with mental paper folding increases performance in the mental paper-folding task [35]. Such learning effects in mental paper folding can be even enhanced in three-dimensional teaching sessions using virtual environments compared to two-dimensional teaching sessions [36]. To test for learning and to prevent fatigue effects, the study was split into two sessions. Due to learning effects, we expected lower RTs and error rates in the second session than in the first session [35,36].

2. Methods

2.1. Participants

Participants were recruited via student mailing lists and by acquaintances of the experimenters. The 57 male and 42 female participants were between 19 and 35 years old (M = 24.9 years, SD = 3.5). The laterality index assessed with the Edinburgh Handedness Inventory [37] ranged from −100 to +100 (M = 65.7, SD = 57.7), indicating mainly right-handers. All participants gave informed consent, and the study was conducted in accordance with the Belmont Report [38].

2.2. Creation of the Stimulus Material

Example stimuli are shown in Figure 1. Stimulus creation was carried out by the following steps: At first, 10 base grids were created (note that 11 base grids are possible for a cube. However, the 11th grid would have been in a 2 × 5 table, whereas the other 10 fitted into a 3 × 4 table), which differed in the arrangement of six squares (3.8 cm × 3.8 cm). Then, all overlapping solutions requiring at least two folds were created. Overlapping lines in the cube were highlighted with yellow lines. The most central square between the yellow lines was then filled with a dashed pattern to later indicate the basis of the cube. For each overlapping solution, the yellow lines were switched within the same square to create no overlaps. This resulted in 107 stimuli in total (38 overlaps and 69 no overlaps). During the experiment, each stimulus was rotated to 90, 180, and 270 degrees (total of 428 stimuli).

2.3. Task and Procedure

The experiment was run on the participants' personal notebooks using OpenSesame 3.25 [39]. The experiment file is available at https://osf.io/tj8h2 (accessed on 11 November 2022). To maintain the participants' attention, the experiment was split into two sessions of 30–60 min each. In both sessions, participants started with one familiarization trial of a randomly selected stimulus. Participants were told that the grid illustrates a sheet of paper that can be folded into a cube with the dashed square as its basis. They were instructed to estimate as quickly and correctly as possible whether the highlighted lines in yellow would overlap in such a cube. They were asked to press the 'X' key with their left index finger to indicate an overlap, and to press the 'M' key with their right index finger to indicate no overlap, which was visually guided by a green 'X' button on the left and a red 'M' button on the right side of the screen. After the familiarization trial, participants received feedback about their RT and whether their responses were correct. This was followed by a block of 214 trials per session in which the stimuli were randomly presented. A fixation dot was presented for 1 s before each stimulus appeared on the screen. Participants' responses triggered the presentation of the next fixation dot. A short break of at least five seconds was introduced after every 20 trials.

(**a**) (**b**)

Figure 1. Depiction of the stimuli: (**a**) The stimulus requires three imaginative folds without directional changes. The highlighted (yellow) lines overlap in the imagined cube. (**b**) The stimulus requires five imaginative folds with four directional changes. The highlighted lines do not overlap in the imagined cube.

2.4. Data Analysis

RT was defined as the interval between the presentation of the stimulus and the participants' response. From 42,372 observations, 28 RTs were below 200 ms and 3 RTs were above 1 min, which were replaced by individuals' mean RT of this stimulus (of the other 3 rotational angles). The error rate indicates the percentage of incorrect responses. Mean RTs and error rates were calculated for each stimulus categorization. Stimuli were categorized by overlaps (overlap or no overlap), the number of relevant folds (3, 4, or 5), and the number of directional changes (0, 1, 2, 3, or 4). RTs and error rates were analyzed using repeated measures ANOVAs. If Mauchly's test indicated that the assumption of sphericity was violated, Huynh–Feldt-corrected degrees of freedom and p-values were reported. Further comparisons were conducted using t-tests with Sidak-adjusted pairwise comparisons. Whenever appropriate, minimum (p_{min}) or maximum (p_{max}) significance values were reported. For separate analyses of male and female participants see supplemental material.

To investigate learning effects, two-paired sample t-tests were calculated using the mean RT and mean error rate of each session. For all analyses, the probability of the type-one error was $\alpha = .05$. Data, along with the syntax for data analyses, are available at https://osf.io/tj8h2 (accessed on 11 November 2022).

3. Results

3.1. Reaction Times

An ANOVA with the within-factors *overlap* (overlap or no overlap), *folds* (3, 4, or 5), and *directional changes* (fewer or more) was calculated for RTs. Means and standard errors of RTs are shown in Figure 2. Statistical values of the ANOVA are shown in Table 1.

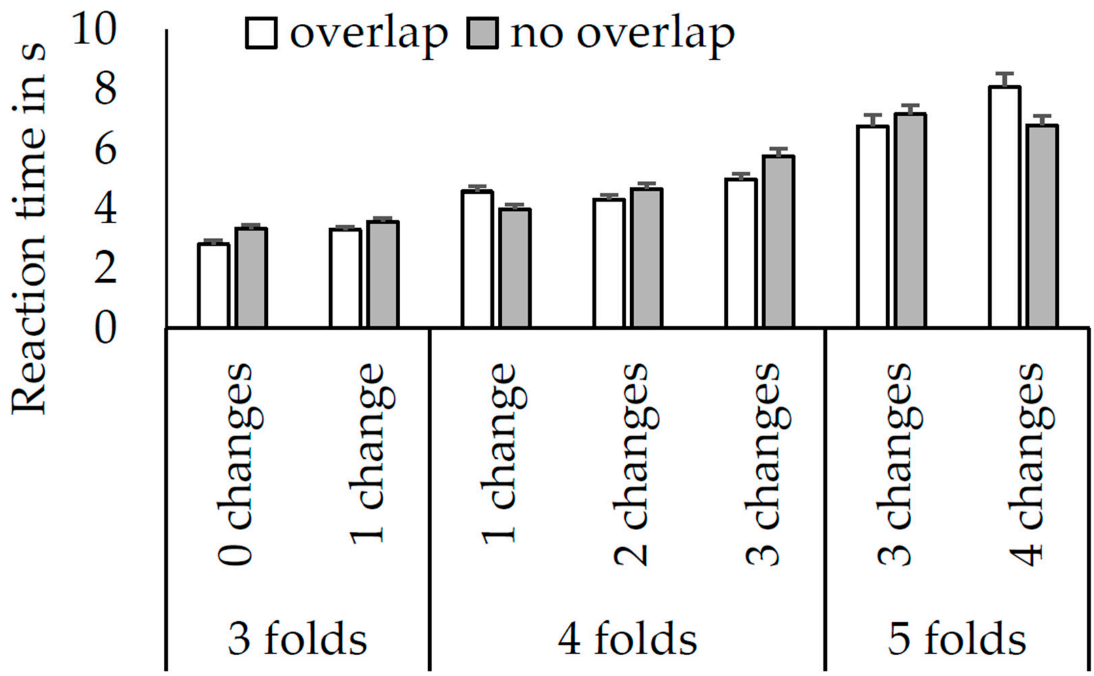

Figure 2. Means and standard errors of reaction times (in seconds), depending on the number of relevant *folds* (3, 4, or 5), the number of *directional changes* (0, 1, 2, 3, or 4), and whether the highlighted lines *overlap* in the cube (overlap or no overlap). To maintain an equal number of factor levels, the data of four folds and two changes were not used in the ANOVA.

Table 1. Statistical results of the ANOVA for reaction times. The ANOVA was conducted with the factors *overlap*, *folds*, and *directional changes*.

	F	*df1, df2*	*p*	η^2_p
Overlap	<0.1	1, 98	.881	<.01
Folds	220.7	1.1, 106.3	<.001	.69
Changes	65.9	1, 98	<.001	.4
Overlap × folds	10.1	1.2, 119.7	.001	.09
Overlap × changes	1.8	1, 98	.18	.02
Folds × changes	9.8	1.8, 174.4	<.001	.09
Overlap × folds × changes	30.6	1.2, 117.4	<.001	.24

The significant main effect *folds* indicated significantly longer RTs with five folds (M = 7.2 s) than with four folds (M = 4.8 s; $p < .001$) and significantly shorter RTs with three folds (M = 3.2 s; $p_{max} < .001$). The significant main effect *directional changes* was modified by the significant interaction between *overlap*, *folds*, and *directional changes*. This indicated that the RTs were significantly longer with more directional changes than with fewer directional changes ($p_{max} = .015$), except for five folds with no overlap, where this pattern was reversed ($p = .033$).

3.2. Error Rates

An ANOVA with the within-factors *overlap* (overlap or no overlap), *folds* (3, 4, or 5), and *directional changes* (fewer or more) was calculated for error rates. Means and standard errors of the error rates are shown in Figure 3. Statistical values of the ANOVA are shown in Table 2.

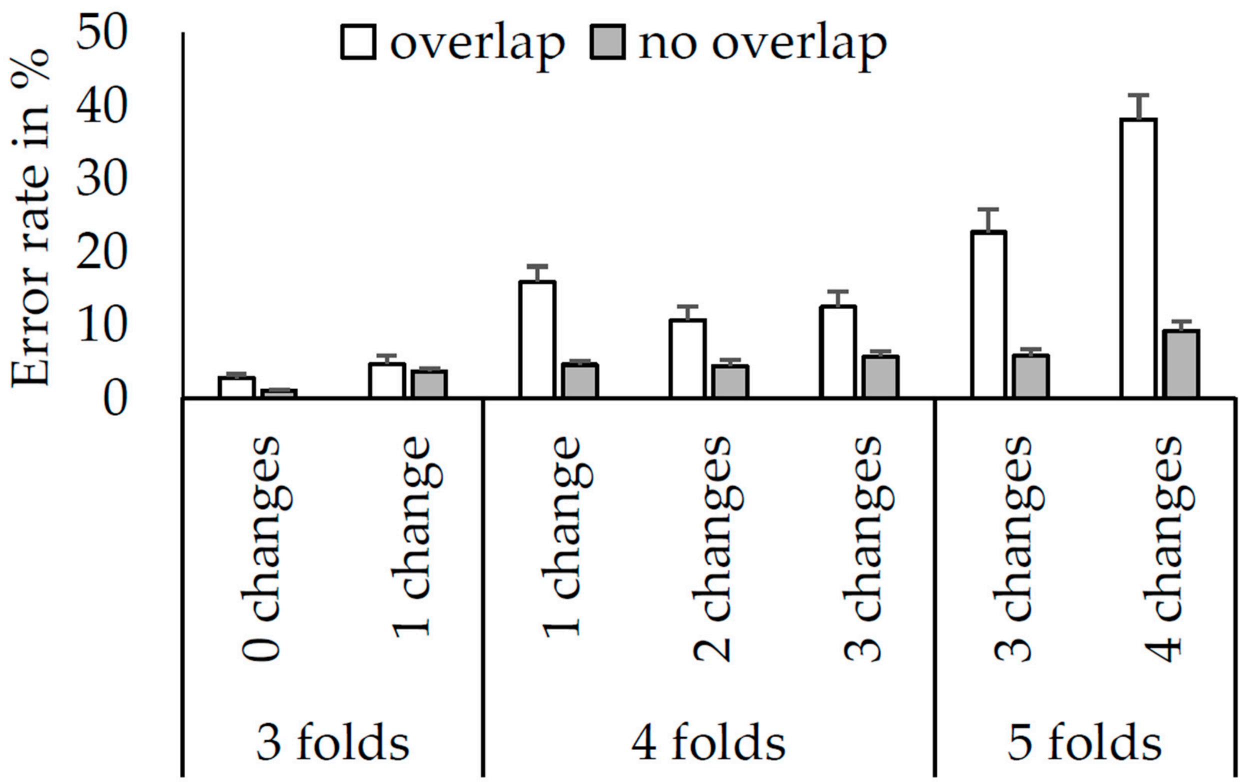

Figure 3. Means and standard errors of error rates (in %), depending on the number of relevant *folds* (3, 4, or 5), the number of *directional changes* (0, 1, 2, 3, or 4), and whether the highlighted lines *overlap* in the cube (overlap or no overlap). To maintain an equal number of factor levels, the values of four folds and two changes were not used in the ANOVA.

Table 2. Statistical results of the ANOVA for error rates. The ANOVA was conducted with the factors *overlap*, *folds*, and *directional changes*.

	F	*df1, df2*	*p*	η^2_p
Overlap	60.3	1, 98	<.001	.38
Folds	91.5	1.5, 150.2	<.001	.48
Changes	26	1, 98	<.001	.21
Overlap × folds	53	1.5, 144.4	<.001	.35
Overlap × changes	3.4	1, 98	.068	.03
Folds × changes	18.1	1.5, 142.8	<.001	.16
Overlap × folds × changes	12.9	1.2, 129.3	<.001	.12

The significant main effect *folds* was modified by the significant interaction between *overlap*, *folds*, and *directional changes*. This indicated significantly higher error rates with five folds than with four folds, and significantly lower error rates with three folds (p_{max} = .049), except for one comparison with no overlaps and few changes (p = .467). The significant main effect *directional changes* was modified by the significant interaction between *folds* and *directional changes*. This indicated that the error rates were significantly higher with more directional changes than with fewer directional changes with three folds (p_{max} = .031) and five folds (p_{max} = .018), but not with four folds (p_{min} = .054). The significant main effect *overlap* was modified by the significant interaction between *overlap*, *folds*, and *directional changes*. This indicated significantly higher error rates with overlaps than with no overlaps (p_{max} = .001), except for three folds with one directional change. Furthermore, the significant interaction between *folds* and *overlap* indicated that the difference between overlaps was significantly larger with five folds (ΔM = 22.9%) than with four folds (ΔM = 9.1%, p < .001), and significantly lower with three folds (ΔM = 1.4%; p_{max} < .001).

3.3. Learning Effects in Mental Paper Folding

To analyze learning effects, paired-samples *t*-tests were calculated for RT and error rates. Means and standard errors of RTs and error rates are shown in Figure 4. RTs were significantly shorter in Session 2 than in Session 1 (t (98) = 14.6, $p < .001$, 95% CI [1.2 s, 1.6 s], $d = 1.47$). Similarly, error rates were significantly shorter in Session 2 than in Session 1 (t (98) = 6, $p < .001$, 95% CI [1.2 s, 2.4 s], $d = 0.6$).

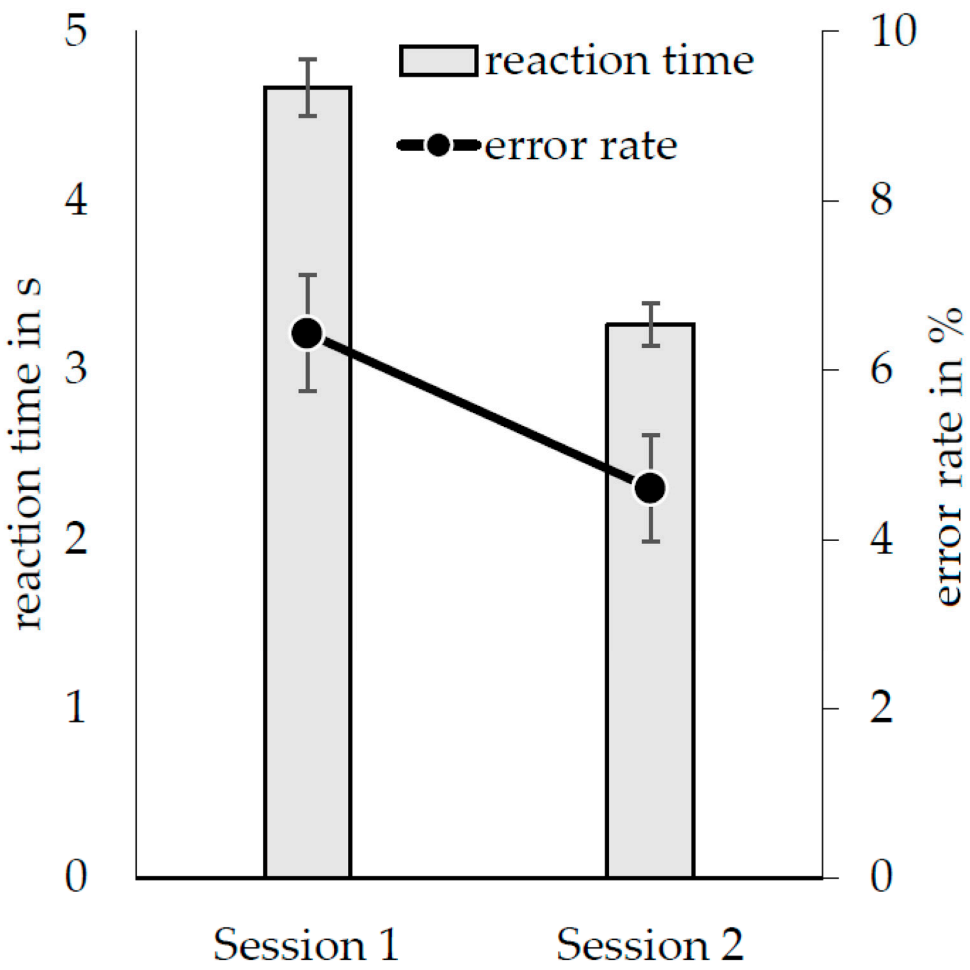

Figure 4. Means and standard errors of reaction times (in seconds) and error rates (in %) in Session 1 and Session 2.

4. Discussion

The principal object of investigation of the present study refers to action imagery effects in the mental paper-folding task. It was expected that the task would implicitly require the use of action imagery to mentally create a cube from a two-dimensional stimulus. The results indicated that the RTs increased with the number of imagined folds and the number of imagined directional changes, while the potential overlap did not significantly influence the RTs. In contrast, the error rates were significantly longer with overlaps than with no overlaps. Furthermore, as with the RTs, the error rates increased with the number of imagined folds and the number of imagined directional changes.

It was expected that the participants would not fully fold the cube in their imagination, but only those parts necessary to decide whether the lines would overlap or not [33]. As in previous studies, increased error rates indicated an increase in task difficulty with more imagined folds [20]. In addition to error rates, the RTs increased with the least number of imagined folds required to give a valid response. Similar results have been observed in studies showing that imagined walking durations increase with the walking distance [40], and that imagination durations increase with the number of button presses [7]. This stands in contrast to a previous study showing the use of heuristic problem-solving strategies in mental paper folding [20]. However, in the previous study, participants imagined folding, imagined punching a whole, and imagined unfolding the paper. By providing multiple-choice visual solutions, heuristic rules were more likely because they allowed for discarding logically implausible solutions for some items [20]. In the present study, using a two-choice task, heuristic rules were rather unlikely at the beginning of the experiment but could have been acquired while familiarizing with the task during the experiment (e.g., two lines match if set opposed to one another with three squares in between). This may have shortened RTs and increased response accuracy. Nevertheless, it appears unlikely that heuristic strategies that do not involve action imagery would have increased RTs systematically with the number of relevant folds [34]. Furthermore, using heuristic rules implicated higher error rates than using imagery to solve the task [20]. Therefore, participants in the present study most likely used imagination processes in which the paper was folded in a stepwise manner [15].

RTs and error rates increased with the number of directional changes during mental paper folding, indicating that task difficulty increased not only with the number of relevant folds, but also with the number of directional changes. During actual folding, such an increase in RTs would have been expected because the directional change requires a 90° turn of either the hands or the sheet of paper to continue folding. Most likely, imagination of such a turn increased RTs. Such an explanation implies action imagery from a first-person perspective rather than imagery that does not involve perception of a human action [41–43]. Again, abstract problem-solving strategies [34] would not have predicted such an increase in RTs. Hence, this novel finding is consistent with the assumption that action imagery is used to solve the mental paper-folding task, even in the absence of explicit imagery instructions.

Error rates were larger with overlaps than with no overlaps. Hence, overlaps were more difficult to solve than no overlaps. In contrast to the error rates, this was not observed with respect to RTs. Most likely, the time-consuming imagination process of mentally folding each step does not differ between overlaps and no overlaps. Error rates may have been larger with overlaps than with no overlaps because the overlaps required a more detailed focus on the final part of the imagination. Hence, after the cube had been mentally folded, the decision as to whether the lines would overlap was more difficult. One may argue that the lines were closer together with overlaps than with no overlaps. However, this should have led to a significant increase in RTs for overlaps as well, which was not observed. An alternative explanation could be that the probability for overlapping stimuli in the material was only 36%. With participants noticing this probability during the experiment, this may have led to a simple strategy of selecting no overlaps under uncertainty, which accounts particularly for difficult items. Furthermore, the difference in error rates between overlaps and no overlaps increased with the number of relevant folds. To speculate, this may indicate processes of imagery maintenance [14,32], i.e., that the more folds that have been mentally performed, the harder it is to maintain the imagined cube to make the final decision.

In line with previous observations, RTs and error rates indicated strong learning effects in spatial thinking of practiced and unpracticed tasks [44]—and more specifically in the mental paper-folding task [35]. Learning effects should be considered when using the mental paper-folding task for ability assessments in the future. It is possible that the learning effects were particularly high in the present study due to the high number of items ($k = 428$). In addition to a smaller item pool, assessments of imagery ability may take parallel versions into account to reduce learning effects that are based on item familiarity. Nevertheless, this may not prevent general improvements in action imagery ability [35,44]. For instance, it has been shown that practicing the mental paper-folding task improves performance in the mental rotation task, and vice versa [35]. This is not surprising, as the two tasks correlate strongly (r = .61) [45], indicating a common construct (e.g., action imagery ability).

Most likely, the mental paper-folding task involves only visual action imagery [15], but no other modalities (e.g., haptics, kinesthesis, acoustics) that are relevant for action imagery ability [14,32]. Future studies may focus on participants' strength of representation of various modalities. For this, after mental paper folding, participants may report on rating scales how strongly they focused on these modalities [8].

Furthermore, participants' expectations [46] may have influenced their responses in a way similar to self-fulfilling prophecy [47]. To control for expectations, future studies may ask participants about what parameters might influence the timing or the correctness of their responses. It would be interesting to see how many would name the number of relevant folds and the number of directional changes. This would speak against the involvement of action imagery if directional changes only influence the responses (i.e., timing or correctness) in those participants who are aware of this parameter and expect it to influence their responses, but not in those who are unaware of this parameter.

Spontaneous verbal reports occurred during the assessment of some participants when they occasionally and unintentionally pressed the wrong key, despite knowing the correct answer (all data of wrong key presses were included in the analysis. Spontaneous interactions between participants and experimenters were not planned beforehand and, therefore, not integrated in the data). Although not appropriate, some participants may have corrected their previous response, thereby already responding to the subsequent stimulus. To avoid overhasty responses in the future, longer intertrial intervals could be introduced between stimuli. Apart from that, one may argue that the high error rates in some participants were not due to low imagery abilities, but due to low experimental commitment. Clicking through the items without intentions to give correct responses would indeed result in high error rates. However, in the data for each individual subject, we checked whether the participant responded consistently with the same key or whether a block of very fast responses (<200 ms) occurred, so as to exclude potential subjects with low experimental commitment.

Action imagery ability might involve both action-specific abilities and general abilities that apply for any action [48,49]. Hence, it remains to be investigated whether imagery ability that is measured with the mental paper-folding task is generalizable to other more complex actions that involve the whole body. Furthermore, it would be interesting to investigate action imagery ability in patients with apraxia. One might expect lower imagery ability in patients with apraxia than in healthy controls, as has been shown in a single case study using a hand laterality judgment task [50]. Moreover, we would expect differences between patients and healthy controls to be larger in objective measures such as the mental body-rotation task [51] or the presented mental paper-folding task than in questionnaires that are prone to self-rating biases [14]. Nevertheless, it could be interesting to investigate potential correlations with existing questionnaires on action imagery ability [52], such as the Vividness of Movement Imagery Questionnaire [48,53].

5. Conclusions

In conclusion, our results support the assumption that visual action imagery is a key process in solving the mental paper-folding task [33]. Particularly, the increase in RTs caused by the increase in the number of relevant folds indicates a stepwise mental folding process [15]. Most likely, all imagery subdimensions are involved in mental paper folding [30,32]. Image generation is supported by the visual input of the two-dimensional grid. The imagined action of folding then involves image transformation. Particularly in stimuli with several folds, image maintenance is needed to keep the last imagined transformation in mind. Finally, details of the image (i.e., the highlighted lines) are inspected to come to a decision about the possible overlap.

Although it appears rather doubtless that visual action imagery is involved in mental paper folding, the origin of the action remains unresolved. One does not need to necessarily imagine oneself as an actor. During the imagination process, the paper could also be folded by a magic hand or remotely controlled. The latter would be a mental object transformation rather than action imagery. However, mental object transformations should not be influenced by directional changes and could even occur simultaneously for folding steps. Therefore, the increase in RTs with the number of relevant folds and the number of directional changes strongly supports the assumption of action imagery processes in the mental paper-folding task that are similar to those used in actual execution [5,15].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/psych5010002/s1, Figure S1: Means and standard errors of reaction times (in s) depending on the number of folds (3, 4, 5), the number of direction changes (0, 1, 2, 3, 4), and whether the highlighted lines overlap in the cube (overlap, no overlap) in female and male participants: Figure S2: Means and standard errors of error rates (in %) depending on the number of folds (3, 4, 5), the number of direction changes (0, 1, 2, 3, 4), and whether the highlighted lines overlap in the cube (overlap, no overlap) in female and male participants; Figure S3: Means and standard errors of reaction times (in s) and error rates (in %) in Session 1 and Session 2, separately for female and male participants; Table S1: Statistical results of the ANOVA on reaction times: Table S2: Statistical results of the ANOVA on error rates.

Author Contributions: Individual contributions of authors were as follows: conceptualization, S.F.D.; methodology, S.F.D.; validation, S.F.D.; formal analysis, S.F.D.; investigation, S.F.D.; data curation, S.F.D.; writing—original draft preparation, S.F.D.; writing—review and editing, S.F.D., and C.D.; visualization, S.F.D. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data is contained within the article and supplementary material. Data exclusions, manipulations, and all measures in the study are reported in the manuscript. Stimulus material and data are available via the following link: https://osf.io/tj8h2/ (accessed on 11 November 2022).

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