Catch the star! Spatial information activates the manual motor system

A. Miklashevsky

1 Potsdam Embodied Cognition Group, University of Potsdam, Germany

*Correspondence: Alex Miklashevsky
armanster31@gmail.com

Abstract
Previous research demonstrated a close bidirectional relationship between spatial attention and the manual motor system. However, it is unclear whether an explicit hand movement is necessary for this relationship to appear. A novel method with high temporal resolution – bimanual grip force registration – sheds light on this issue. Participants held two grip force sensors while being presented with lateralized stimuli (exogenous attentional shifts, Experiment 1), left- or right-pointing central arrows (endogenous attentional shifts, Experiment 2), or the words "left" or "right" (endogenous attentional shifts, Experiment 3). There was an early interaction between the presentation side or arrow direction and grip force: lateralized objects and central arrows led to a larger increase of the ipsilateral force and a smaller increase of the contralateral force. Surprisingly, words led to the opposite pattern: larger force increase in the contralateral hand and smaller force increase in the ipsilateral hand. The effect was stronger and appeared earlier for lateralized objects (60 ms after stimulus presentation) than for arrows (100 ms) or words (250 ms). Thus, processing visuospatial information automatically activates the manual motor system, but the timing and direction of this effect vary depending on the type of stimulus.

**Keywords:** spatial attention, spatial processing, endogenous attention, exogenous attention, motor system, grip force
Catch the star! Spatial information activates the manual motor system

Introduction

The manual motor system and orienting of spatial attention are closely related. Eye-hand coordination enables efficient reaching, grasping, and object manipulation. This coordination requires analyzing visual information about the environment surrounding hands and simultaneous control of ongoing hand movements (see for review 1).

Attention can prioritize spatial locations already before the execution of a hand movement. This effect was shown in a series of experiments where participants pointed at different locations on a screen and then reported a briefly presented target symbol (2,3, see also 4). Notably, the target symbol was presented either in a position later pointed at or in a different position. Participants were significantly more accurate at identifying the target symbol when it was presented in a to-be-pointed-at location.

Eye-hand coordination is a complex bidirectional process and not merely serial delivery of motor commands to the execution level after complete analysis of visual information. Multiple target coordinates are averaged and influence the ongoing movement, constantly updating the motor program (5,6, see 7, for a theoretical account).

In line with this research is the so-called near-hand effect (8): attention is more engaged when objects appear close to hands. Participants more efficiently inhibit distractors presented farther away from hands (9) and identify new objects in the near-hand space faster (10, see 11, for a review). Hand movements lead to dynamic changes of the near-hand space, which results in faster detection of targets closer to hands at every moment (12). Also, the task and type of stimuli matters: having one’s hand close to words or arithmetical expressions is disadvantageous for semantic processing of those symbolic stimuli (13,14).

Thus, previous research convincingly demonstrated a bidirectional relationship between spatial attention and hand movement across various paradigms. But how automatic is this link between the manual motor system and spatial processing? Is hand movement, whether ongoing or potential, a
necessary component for this relationship to appear? In a previous study, my colleagues and I
presented participants with large vs. small numerical stimuli (15) while monitoring participants’
spontaneous hand motor activity using two grip force sensors (16–20, for review and methodological
details, see 21). No manual response or explicit hand movement was required. Numerical cognition
research shows that small numbers are associated with the left peripersonal space, and large numbers
are associated with the right peripersonal space (Spatial Numerical Association of Response Codes, or
SNARC effect, see 22). This effect has been demonstrated with button press responses, finger
movements (23), eye movements (24), foot responses (25), and even full-body movements (see for
reviews 26,27, see for meta-analysis 28). Despite this overwhelming evidence for the presence of
spatial-numerical associations, we found no SNARC effect in grip force (15), either because no
attentional shifts appeared without explicit motor responses to numeric stimuli (cf. 29) or because the
manual motor system is not activated automatically by spatial information. The latter hypothesis was
tested explicitly in the present study.

The goal of the present study was to investigate the direct effects of attentional shifts on the manual
motor system in the absence of any motor action. A novel method, bimanual grip force recording,
allows monitoring motor activity in hands with millisecond resolution while participants process visual
stimuli. Grip force sensors measure spontaneous motor activity during action observation (30) and
semantic processing of motor-related language (16–20). Both hands exhibit comparable activity in
response to motor-related linguistic stimuli (31).

In the present study, I recorded grip force bimanually while manipulating participants’ visual attention.
Specifically, exogenous and endogenous attentional shifts (see 32,33) were induced using different
types of stimuli. Lateralized stimuli cause exogenous attentional shifts by summoning attention as they
are physically present at a particular location. In the present study, exogenous attentional shifts were
induced by presenting participants with left- or right-localized stars (Experiment 1). In contrast,
centrally presented symbolic stimuli direct attention by their meaning and thus lead to endogenous
attentional shifts. In the present study, endogenous attentional shifts were induced by presenting
participants with left- or right-pointing arrows (Experiment 2) or words "left" and "right" (Experiment 3). Words produce attentional effects different than those resulting from arrows. While some authors assumed that both arrows and linguistic cues cause similar endogenous attentional shifts (e.g., 33), more recent studies demonstrated essential differences between these types of cues (34). A series of studies showed that words with a typical localization in vertical space (e.g., shoe, grass, sun, or cloud) could shift attention in the corresponding direction (35–37). This effect extends even to abstract concepts, such as god or devil (38). Simple linguistic cues (e.g., the word up) can also modulate trajectories of vertical saccades (39).

Additionally, bimanual grip force recording has a high temporal resolution (1000 Hz), making it possible to reveal the precise timing of manual motor activity accompanying attentional shifts. I expected the effect of interest to emerge later for symbolic stimuli (arrows and words) than for physical objects (stars), since symbols require one additional processing step – extraction of meaning – for causing attentional shifts.

**GENERAL METHOD**

Forty-two psychology and linguistics students (14 males, 28 females) of the University of Potsdam participated in the study for course credit. An entire testing session consisted of four experiments: lateralized star presentation (Experiment 1), lateralized sound presentation (not reported here\(^1\)), central arrow presentation (Experiment 2), and word presentation (Experiment 3). All experiments were conducted in a pseudorandom order to exclude possible systematic sequence or fatigue effects. The exact order of experiments is specified for every participant in supplementary materials (see data availability statement). Participants were allowed to take breaks between experiments, walk and drink water. The whole testing session lasted between 60 and 90 minutes.

---

\(^1\) The force pattern generated by sound presentation was strikingly different from those resulting from other types of stimuli: sounds lead to a clear initial dip in force followed by one short and one very long peak, probably correlating in magnitude with sound intensity. It seems that qualitatively different processes are reflected in grip force in this case.
After the experiments, participants completed questionnaires including demographic data (gender, age, native language, and foreign languages they speak) and physiological data (seeing problems, hearing problems, motor diseases, and whether they take medications that can influence motor control). Additionally, participants filled in the Edinburg Handedness Inventory (EHI, 40), where original instructions were replaced with a more intuitive Likert scale as suggested elsewhere (41). Resulting EHI scores range from +100 (exclusively right-handed) through 0 (ambidextrous) to -100 (exclusively left-handed). All participants signed an informed consent form before the study. The study was approved by the Ethics Committee at the University of Potsdam (www.uni-potsdam.de/de/senat/kommissionen-des-senats/ek; study number 15/2019).

One participant was excluded due to a self-reported motor problem (light essential tremor) clearly reflected in his force data. Another participant reported left leg paralysis, but her data were not qualitatively different from the rest of the sample and thus remained in the final dataset. Only German native speakers participated in the word presentation study (Experiment 3). All but one participant reported having normal or corrected-to-normal vision.

**Equipment and data acquisition**

The method followed closely the one recommended by Nazir et al. (21) for single-sensor recording. Both sensors were stand-alone load cells manufactured by ATI Industrial Automation, USA (www.atiia.com/Products/ft/sensors.aspx). They resembled large metal coins with 40 mm diameter and 14 mm height, and each weighed 57 g. Each sensor was covered from both contact sides with a 3 mm plastic cover of the same diameter as the sensor itself (40 mm), resulting in a total thickness of 20 mm and a total weight of 65 g per sensor (see Figure 1). These sensors record force dynamics with millisecond resolution along three orthogonal axes, but only Fz force along the vertical axis through the sensors was analyzed and reported here. Two PCs were used: one for running the experiment under OpenSesame software (42) and another for force data acquisition under Expyriment software (43). The first PC sent a trigger at the beginning of each trial to later identify a corresponding time point in the
force data file. Monitor Philips Brilliance LCD 220P4LPY 22” with a screen resolution 1680x1050 was used for stimuli presentation.

Fig. 1. Experimental setup and equipment. Panel A. Bimanual force recording setup. Panel B. Grip force sensor (X – longitudinal, Y – radial, Z – compression forces). C. The way participants held the sensors (around 45° relative to the table surface, not strictly controlled). Adapted image from Miklashevsky et al. (15, Fig. 2).

Participants sat at a desk and held one sensor in each hand at an angle of around 45° relative to the table surface with the thumb on one side and the index and middle fingers on the other side. Participants’ elbows rested on the table while their hands held the sensors, thus preventing sensor slippage (see Fig. 1). The distance between sensors varied from 30 to 50 cm and was not strictly controlled, but both were equidistant from each participant’s mid-sagittal plane. The distance from participants’ eyes to the screen was around 60 cm.

Before data collection, participants practiced applying a holding force in a range between 1.5 N and 3 N with each hand. The sensors were represented on the screen as two circles that changed their color from green ("too weak") to red ("too strong") with the pre-defined force range indicated by the grey color. As soon as participants managed to turn both circles into grey, they received an instruction to keep the force at this level during the whole testing session. Data collection started automatically after participants held the sensor with the required force for three seconds without crossing these thresholds. This calibration procedure was repeated after each break and at the beginning of each experiment. Most participants successfully learned to perform the calibration within 15-30 seconds. There were, however, a few participants who required up to two minutes during the first calibration. There was no cover story used for the participants.
Experiment 1: Star presentation

Participants were presented with either central or lateralized (left vs. right) visual stimuli in this experiment. This ensured exogenous control over attention (33), while bimanual force recording allowed investigating the dynamic involvement of the motor system in the processing of spatial information.

Participants

Forty-one psychology and linguistics students (13 males, 28 females; mean age = 24 years) participated in the experiment. Their mean EHI score was 66 (80% had EHI score > 50; 10% had EHI score between +50 and -50; 10% had EHI score < -50). All but one participant reported normal or corrected-to-normal vision. No participant took medications affecting motor control.

Stimuli and design

Red and yellow stars were used as stimuli in catch (go) and critical (no-go) trials accordingly. The background was kept black. Stimuli can be found in the supplementary data (see data availability statement). Stars appeared in the middle of the screen, on the left or the right side. Grip force was recorded bimanually. This results in a 2 (Hand: left / right) X 3 (Position of the star: left / central / right) within-participant design.

Task and procedure

After the calibration procedure described above, the experiment started. Each trial consisted of a fixation dot (200 ms), followed by a stimulus (until response, but no longer than 2000 ms). The stimuli were stars around 4 cm in diameter (3.82 degrees of visual angle calculated by using the formula 57.3*w/d; w – width of the object; d – distance to the object), which appeared with equal probability (33%) in one of three positions: at the center of the screen, or 19.5 cm left or right from the center (18.62 degrees of visual angle). 75% of the stars were yellow, and red stars appeared in 25% of all
trials. The task was to say "yes" when a red star appeared, regardless of stimulus location. Participants were asked not to rotate their heads when stars appeared laterally, but eye movements were allowed. Additionally, participants were instructed not to cross their legs during the experiment. Critical trials for analysis were no-go trials (yellow stars). This means that overt motor or verbal responses do not contaminate grip force recordings. Such responses typically generate large artifacts in these recordings (e.g., see panel A at Figures 2, 4, and 6). The experiment consisted of 360 trials with a break in the middle and lasted around 15 minutes. It was preceded by a short practice (12 trials).

Data preprocessing and analysis

The preprocessing of grip force data closely followed the recommendations of Nazir et al. (21, Experiment 2). Data were filtered at 15 Hz before analysis with a fourth-order, zero-phase, low-pass Butterworth filter. Single epochs were extracted from the vertical Fz signal, starting 200 ms before and ending 1000 ms after stimulus onset. The global variation\(^2\) in force across the experiment was corrected by (1) averaging force within a 20 ms interval before stimulus onset in each epoch and (2) subtracting this average force from the entire epoch. As a result, grip force always crosses the zero point at the start of each trial, and negative force values reflect a vertical grip force less than that at the moment of stimulus presentation, not the absence of force. Maximum and minimum thresholds were applied (±500 mN) to remove movement artifacts and identify participants with unacceptably large force variability. The proportion of trials where force exceeded one of the thresholds varied across participants from 0% to 19% (mean = 2%). Those trials were discarded, but no participant was excluded due to this criterion. Accuracy varied from 98% to 100% (mean = 100%); error trials were excluded from further analysis.

Overall grip force patterns are presented in Figure 2 to give readers an overview of this relatively unfamiliar data type. The blue line in Figure 2A represents averaged force of both hands for

\(^2\) Under global force variation, I understand here stimulus-unrelated changes in force over longer periods of time, e.g., if participants press sensors stronger due to higher arousal at the beginning of the experiment or slightly release the sensors in the second half of the session due to fatigue, etc.
all accepted no-go trials. As suggested before (15), these changes will be referred to as H (high force, peaks), with a number representing a time point. For example, H130 means a peak with its highest point at around 130 ms after stimulus onset. As one can see, independently of a particular condition, grip force produces three peaks (H130, H330, and H600). The second peak (H330) is the tallest. Figure 2B represents averaged grip force changes in go (dotted red line) and no-go (solid blue line) trials. These two lines start diverging at 250 ms after stimulus onset with force in go trials reaching its highest point (almost 50 mN) at around 750 ms and remaining at this level till the end of the epoch (1000 ms). Figure 2C represents force averaged by condition (Hand and Position): red lines represent right-hand forces, blue lines represent left-hand forces; dotted lines represent the star-left condition, solid lines the star-in-the-center, dashed lines the star-right condition.

**Fig. 2. Grip force changes (in milli-Newton) plotted against time from stimulus onset (in milliseconds), Experiment 1.** Panel A. Averaged force profiles across all accepted no-go trials of all participants. Panel B. Force profiles in go (dotted red line) and no-go (solid blue line) trials. These forces diverge around 250 ms after stimulus presentation. Panel C. Force profiles averaged by condition (Hand X Position). Light-yellow areas (60-130 ms and 260-1000 ms) indicate interactions between Hand and Position, green area (820-1000 ms) indicates the main effect of Hand. Red lines represent right-hand forces, blue lines – left-hand forces. Dotted lines represent the star-left condition, solid lines – star-in-the-center condition, dashed lines – star-right condition.

The method used by Miklashevsky et al. (15) was applied to identify time windows of interest: forces were aggregated by Hand (left / right) and Position (right/central/left) within participants (see Figure 3A). With Hand (left / right) and Position (left / center / right) as within-variables and interaction
between them, these data were submitted to a cluster permutation analysis\(^3\) (44, package “permuco”, see 45). Five thousand permutations were performed, and TFCE (Threshold-Free Cluster Enhancement) correction for multiple comparisons was used. The analysis revealed four time windows with significant or close to significance effects: main effect of Hand (820-1000 ms after stimulus onset), main effect of Position (680-760 ms), and two time windows with interactions between Hand and Position (60-130 ms and 260-1000 ms after stimulus onset).

Fig. 3. Grip force changes (in milli-Newton) averaged by Hand and Position, Experiment 1. Panel A. Average forces in time widow 60-130 ms. Panel B. Average forces in time widow 260-1000 ms. Whiskers represent standard errors.

820-1000 ms, Model 1.1. The data (averaged by Hand and Position for each participant) were then submitted to a linear mixed model analysis using the lme4 package (46) in R. The categorical predictor Hand was sum-coded (left/right, sum-coded contrast -0.5 and 0.5, see 47). Position was re-coded in a continuous manner (left: -1; center: 0; right: 1). Interaction between Hand and Position was included. Participants were included as random factors. I performed a backward elimination using the drop1 function to identify the best-fit model; effects and interactions that did not improve model fit (p > .1) were successively eliminated. Only significant effects are reported unless the effect of interest in a given analysis was non-significant – in such cases, it is also reported.

The main effect of Hand was significant: grip force in the left hand was more prominent than in the right hand (b = -4.261, p = .001). The interaction between Hand and Position was also significant (b = 4.071, p = .009). Still, since this time window is a part of a larger one (260-1000 ms) suggested by the

\(^3\) Cluster permutation analysis is a bootstrapping method for continuous signal. In this analysis, conditions are randomly assigned to epochs, which results in a random data structure. According to newly assigned labels, a t-statistics is calculated. The mass of the clusters exceeding a significance threshold is stored. The procedure is repeated multiple times, with the resulting distribution of random cluster masses that can be found in the dataset. The actual cluster mass is then compared with bootstrapped cluster masses, and the likelihood of the observed result is calculated. I suggest using this method in case of force registration for exploratory purposes to identify potential time windows of interest. Linear mixed-effects models are used in the present study for confirmatory analyses.
cluster permutation analysis for this interaction, it was not examined further. Marginal r-squared (variance explained by fixed effects, see 48) was .041, and conditional r-squared (variance explained by the whole model, i.e., fixed and random effects together) was .451. See Table 1 for further details.

Table 1. Model 1.1. Main effect of Hand on grip force in the time window 820-1000 ms (Experiment 1).

| Random effects: | Name     | Variance | SD  |
|-----------------|----------|----------|-----|
| Participants    | Intercept| 74.890   | 8.654|


### Table 2. Model 1.2. Main effect of Position on grip force in the time window 680-760 ms (Experiment 1).

| Random effects: | Name     | Variance | SD   |
|-----------------|----------|----------|------|
| Participants    | Intercept| 102.000  | 10.100|
| Residual        | b        | 120.100  | 10.960|

| Fixed effects:  | SE       | t-value | p-value |
|-----------------|----------|---------|---------|
| Intercept       | -1.692   | -0.981  | .327    |
| Hand            | -3.331   | -2.384  | .017    |
| Position        | 0.382    | 0.446   | .655    |
| Hand*Position   | 4.291    | 2.507   | .012    |

### 680-760 ms, Model 1.2. The same model and approach were used as before but with averaged force in the time window 680-760 ms as a dependent variable. The effect of Hand was significant (larger force in the left hand: \( b = -3.331, p = .017 \)), as well as interaction between Hand and Position (\( b = 4.291, p = .012 \)). Note that this time window is a part of a larger one (260-1000 ms), where this interaction was investigated in detail (see below). The main effect of Position was not significant (\( b = 0.382, p = .655 \)). Marginal r-squared was .026, and conditional r-squared was .473. See Table 2 for further details.

### 60-130 ms, Model 1.3. The data were restructured, and the mean-centered force of the opposite hand in the same time window was included as a predictor\(^4\). As before, continuously coded Position (-1 = left, 0 = center, +1 = right) was included as fixed effect, participants were included as random intercepts.

---

\(^4\) The force of the opposite hand was used as a predictor in order to account for the correlation of forces due to automatic coordination between hands (49). I expect lateralized stimuli to lead to increased force on the ipsilateral side. Still, at the same time, it is clear from force patterns that the force of both hands changes simultaneously, i.e., when the force of one hand increases, so does the other (see Figures 2C, 6C, and 9C). It implies that this basic physiological mechanism might mask lateralized effects of interest. That is why I suggest using the contralateral force as a covariate and estimating the effect of interest beyond the variance explained by the contralateral force.
Function drop1 was used to identify and successively eliminate non-significant terms. The effect of Position on the left-hand force (after accounting for the contralateral force) was close to significance with higher force when stars were presented on the left side ($b = -0.681$, $p = .052$; marginal $r$-squared = .073, conditional $r$-squared = .726; see Table 3 for details; see also Figure 4).

Table 3. **Model 1.3.** Effect of Position on the left grip force (after controlling for the contralateral force) in the time window 60-130 ms (Experiment 1).

| Random effects: | Name      | Variance | SD  |
|-----------------|-----------|----------|-----|
| Participants    | Intercept | 22.434   | 4.736 |
| Residual        | $b$       | 9.435    | 3.072 |

Fixed effects:

| Name                  | Variance | SD  |
|-----------------------|----------|-----|
| Intercept             | 4.305    | 0.790 |
| Contralateral hand (right) | $0.288$ | 0.074 |
| Position              | $-0.681$ | 0.350 |

| Fixed effects: | Name                  | SE  | t-value | p-value |
|----------------|-----------------------|-----|---------|---------|
| Intercept      | 0.790                 | 5.451 | <.001   |
| Contralateral hand (right) | 0.074 | 3.892 | <.001   |
| Position       | -1.947                | .052 |

Model 1.4. A similar analysis was run with the right-hand force as a dependent variable and Position and mean-centered left force as fixed predictors. This time a strong effect of Position was found with larger right force when stimuli were presented on the right side ($b = 1.316$, $p = .005$; marginal $r$-squared = .371, conditional $r$-squared = .408; see Table 4 for details; see also Figure 4).

Table 4. **Model 1.4.** Effect of Position on the right grip force (after controlling for the contralateral force) in the time window 60-130 ms (Experiment 1).

| Random effects: | Name      | Variance | SD  |
|-----------------|-----------|----------|-----|
| Participants    | Intercept | 1.083    | 1.041 |
| Residual        | $b$       | 17.588   | 4.194 |

Fixed effects:

| Name                  | Variance | SE  | t-value | p-value |
|-----------------------|----------|-----|---------|---------|
| Intercept             | 0.412    | 8.364 | <.001   |
| Contralateral hand (left) | 0.063 | 7.811 | <.001   |
| Position              | 2.839    | .005 |

Fig. 4. Regression lines for the main effect of star position on force (Experiment 1, time window 60-130 ms). See main text for details (Models 1.3 and 1.4).
260-1000 ms, Models 1.5 and 1.6. The same approach was used as for the previous time window (60246 130 ms). Each force was tested separately, with the contralateral force and Position as predictors. This time the effect of Position was significant in both hands: the left force increased when stimuli were presented on the left (b = -1.989, p = .011; marginal r-squared = .053, conditional r-squared = .665; see Table 5) and the right force increased when the stimuli were presented on the right (b = 2.949, p < .001; marginal r-squared = .092, conditional r-squared = .621; see Tables 5 and 6; see also Figure 5).

Table 5. Model 1.5. Effect of Position on the left grip force (after controlling for the contralateral force) in the time window 260-1000 ms (Experiment 1).

| Random effects: | Name          | Variance | SD  |
|-----------------|---------------|----------|-----|
| Participants    | Intercept     |          | 82.810 | 9.100 |
| Residual        | b             |          | 45.420 | 6.740 |
| Fixed effects:  |               |          | SE | t-value | p-value |
| Intercepts      | 1.420         |          | 1.546 | 0.919 | .358    |
| Contralateral hand | 0.217       |          | 0.089 | 2.436 | .015    |
| (right)         |               |          |      |        |         |
| Position        | -1.989        |          | 0.781 | -2.549 | .011    |

Table 6. Model 1.6. Effect of Position on the right grip force (after controlling for the contralateral force) in the time window 260-1000 ms (Experiment 1).

| Random effects: | Name          | Variance | SD  |
|-----------------|---------------|----------|-----|
| Participants    | Intercept     |          | 66.100 | 8.130 |
| Residual        | b             |          | 47.340 | 6.881 |
| Fixed effects:  |               |          | SE | t-value | p-value |
| Intercepts      | -1.992        |          | 1.413 | -1.409 | .159    |
| Contralateral hand | 0.220      |          | 0.086 | 2.545 | .011    |
| (left)          |               |          |      |        |         |
| Position        | 2.949         |          | 0.770 | 3.832 | < .001  |

Fig. 5. Regression lines for the main effect of star position on force (Experiment 1, time window 260-1000 ms). See main text for details (Models 1.5 and 1.6).
To summarize, Experiment 1 demonstrated an early (already at 60-130 ms after stimulus onset) interaction between Hand and Position: lateralized stimuli led to relatively stronger force on the ipsilateral side. However, the effect of lateralized stimuli on grip force was rather asymmetric: the effect of Position was more pronounced in the right hand than the left hand. The same pattern emerged at 260-1000 ms, with even higher significance in both hands.

**Experiment 2: Arrow presentation**

This experiment induced endogenous attentional shifts by centrally presenting arrows (50,51) pointing to the left, right, or both directions, while participants’ grip force was recorded bimanually.

**Participants**

The same sample of participants as in Experiment 1 participated in this experiment.

**Stimuli and design**

Red and yellow arrows were used as stimuli in catch (go) and critical (no-go) trials accordingly. The background was kept black. Stimuli can be found in the supplementary materials (see data availability statement). Arrows always appeared in the middle of the screen and pointed to the left, right, or in both directions. Grip force was recorded bimanually. This results in a 2 (Hand: left / right) X 3 (Direction of the arrow: left / both / right) within-participant design.

**Task and procedure**

After the calibration procedure already described above, the experiment started. Each trial consisted of a fixation dot (200 ms), followed by a stimulus (until response, but no longer than 2000 ms). Participants saw an arrow around 2 cm in diameter (1.91 degrees of visual angle) with equal probability (33%) pointing into one of three directions (left, right, or both). In 25% of all trials, red arrows appeared, the other 75% of arrows were yellow. The task was to say "yes" when a red arrow appeared. Participants were asked not to cross their legs during the experiment. Critical trials were
always no-go trials (yellow arrows). The experiment lasted around 15 minutes and consisted of 360 trials with a break in the middle. A short practice (12 trials) preceded the experiment.

**Data preprocessing and analysis**

The same preprocessing procedures were applied as in Experiment 1. One participant had the proportion of trials with force exceeding pre-defined thresholds (±500 mN) larger than 20% and thus was excluded. For the remaining participants, this proportion ranged from 0% to 10% (mean = 2%). Those trials were discarded. Among preserved participants, accuracy varied from 99% to 100% (mean = 100%); error trials were excluded from further analysis.

Force patterns are shown in Figure 6. The solid blue line in Figure 6A represents averaged force of both hands for all accepted no-go trials. Independently of a particular condition, grip force follows a pattern closely resembling that from Experiment 1 with three peaks (H130, H300, and H650). This time, the first peak (H130) is the tallest. Figure 6B represents averaged forces in go (dotted red line) and no-go (solid blue line) trials. As in the first Experiment, these two lines start diverging at 250 ms after stimulus onset with force in go trials reaching its highest point (around 55 mN) at around 700 ms and remaining at this level till the end of the epoch (1000 ms). Figure 6C represents force averaged by condition (Hand X Direction).

**Fig. 6. Grip force changes (in milli-Newton) plotted against time from stimulus onset (in milliseconds), Experiment 2.** Panel A. Averaged force profiles across all accepted no-go trials of all participants. Panel B. Force profiles in go (dotted red line) and no-go (solid blue line) trials. These forces diverge around 250 ms after stimulus presentation. Panel C. Force profiles averaged by condition (Hand X Direction). Yellow area (100-150 ms) indicates interaction between Hand and Direction; violet area (620-800 ms) represents the main effect of Direction close to significance (p < .1). Red lines represent right-hand forces, blue lines – left-hand forces. Dotted lines represent the arrow-left condition, solid lines – arrow-in-both-directions, dashed lines – arrow-right.
As before, I performed a cluster permutation analysis with Hand and Direction as within-variables.

Five thousand permutations were performed, and TFCE (Threshold-Free Cluster Enhancement) correction for multiple comparisons was used. The analysis revealed a main effect of Direction close to significance in two time windows (510-580 ms and 620-800 ms) and one time window with an interaction between the variables close to significance (100-150 ms; see Figure 7).

Fig. 7. Grip force changes (in milli-Newton) averaged by Hand and Direction in time widow 1001350 ms, Experiment 2. Whiskers represent standard errors.

510-580 ms, Model 2.1. As in Experiment 1, the data (averaged by Hand and Direction for each participant) were then submitted to linear mixed model analysis. The categorical predictor Hand was sum-coded (left/right, sum-coded contrast -0.5 and 0.5). Direction was re-coded in a continuous manner (left: -1; both directions: 0; right: 1). Interaction between Hand and Direction was included. Participants were included as random factors. I performed a backward elimination using the drop1 function to identify the best-fit model; effects and interactions that did not improve model fit (p > .1) were successively eliminated. Only significant effects are reported unless the effect of interest in a given analysis was non-significant – in such cases, it is also reported.

No significant effects or interactions were revealed in this time window. The closest to significance was the main effect of Direction, as demonstrated before in the cluster permutation analysis. The force (non-significantly) decreased for right-pointing arrows compared to left-pointing arrows (b = -1.170, p = .100). Marginal r-squared was .007, and conditional r-squared was .384. See Table 7 for further details.

Table 7. Model 2.1. Main effect of Direction (not significant) on grip force in the time window 510580 ms (Experiment 2).

| Random effects: | Name | Variance | SD |
|-----------------|------|----------|----|
| Participants    | Intercept | 49.62    | 7.044 |
19-80.90 8.994

Fixed effects:

|            | b    | SE  | t-value | p-value |
|------------|------|-----|---------|---------|
| Intercept  | -0.772 | 1.256 | -0.615 | 0.539   |
| Direction  | -1.170 | 0.711 | -1.645 | 0.100   |

620-800 ms, Model 2.2. The same approach was applied as in the previous time window. The effect of Direction was marginally significant (p < .1) and thus remained in the model. Again, the force in both hands slightly decreased for right-pointing arrows compared to left-pointing arrows (b = -1.279, p = .089). The effect of Hand and the interaction between the two variables were not significant. Marginal r-squared was .006, and conditional r-squared was .508. See Table 8 for further details.

Table 8. Model 2.2. Main effect of Direction on grip force in the time window 620-800 ms (Experiment 2).

| Random effects: | Name | Variance | SD |
|-----------------|------|----------|----|
| Participants    | Intercept | 92.23 | 9.604 |
| Residual        | b    | 90.25   | 9.500 |

Fixed effects:

|            | SE  | t-value | p-value |
|------------|-----|---------|---------|
| Intercept  | 1.638 | -0.129 | .898   |
| Direction  | 0.751 | -1.702 | .089   |

Table 9. Model 2.3. Effect of Direction on the left grip force (after controlling for the contralateral force) in the time window 100-150 ms (Experiment 2).
| Random effects: | Name    | Variance | SD   |
|----------------|---------|----------|------|
| Participants   | Intercept | 9.364    | 3.060 |
Table 10. Model 2.4. Effect of Direction on the right grip force (after controlling for the contralateral force) in the time window 100-150 ms (Experiment 2).

| Random effects: | Name     | Variance | SD  |
|-----------------|----------|----------|-----|
| Participants    | Intercept| 13.303   | 3.647 |
| Residual        | Intercept| 9.688    | 3.112 |

| Fixed effects: | b         | SE      | t-value | p-value |
|----------------|-----------|---------|---------|---------|
| Intercept      | 4.663     | 0.643   | 7.253   | < .001  |
| Contralateral hand (left) | 0.767 | 0.072   | 10.638  | < .001  |
| Direction      | 0.867     | 0.349   | 2.486   | .013    |

Fig. 8. Regression lines for the main effect of arrow direction on force (Experiment 2, time window 100-150 ms). See main text for details (Models 2.3 and 2.4).

Thus, Experiment 2 demonstrated a pattern similar to Experiment 1: left- and right-pointing arrows led to a significant force decrease in the contralateral hand. Unlike in Experiment 1, where the effect was stronger in the right hand, the magnitude of the effect in Experiment 2 was comparable across hands. Moreover, the effect of arrow direction was less pronounced and appeared later than the effect of star position.

Experiment 3: Word presentation

In Experiment 3, participants saw centrally presented words LINKS, RECHTS or ZENTRUM ("left", "right" or "center" in German; Note, however, that words "LINKS" and "RECHTS" are adverbs in German, while the word "ZENTRUM" is a noun). Bimanual force recording allowed to investigate dynamic involvement of the motor system into the processing of spatial information presented in a purely symbolic way, i.e., through linguistic meaning.
Participants

Only a subsample of German native speakers participated in this experiment (N = 27; mean age = 24; 9 males and 18 females). On average, participants spoke 1.85 foreign languages, most frequently English, Spanish, and French. The mean EHI score of those participants was +60, with 21 participants (78%) having EHI score > +50, 2 participants (7%) having EHI scores between +50 and -50, and 4 participants (15%) with EHI score < -50. All participants reported normal or corrected-to-normal vision. No participant took medications affecting motor control.

Stimuli and design

Red and yellow words or meaningless symbol arrays (e.g., §@#$%) were used as stimuli in catch (go) and critical (no-go) trials accordingly. The background was kept black. Experimental scripts can be found in the supplementary data (see data availability statement). Grip force was recorded bimanually. This results in a 2 (Hand: left / right) X 3 (Word: left / center / right) within-participant design.

Task and procedure

After the calibration procedure described above, the experiment started. Each trial consisted of a fixation dot (200 ms), followed by a stimulus (until response, but no longer than 2000 ms). Participants saw words or symbol arrays, all having a length of around 2.5 cm (2.39 degrees of visual angle) in a 25 px (19 pt) Droid Sans Mono font. Words "left", "right", and "center" appeared with equal probability. The task was to say "yes" when a red word (20% of all trials) or symbol array (20% of all trials) appeared. Participants were asked not to cross their legs during the experiment. Critical trials were always no-go with words (i.e., only real words in yellow font, 40% of all trials). In the remaining 20% of all trials, yellow symbol arrays appeared, and no response was required. The experiment consisted of 450 trials with a break in the middle and lasted around 20 minutes. A short practice (18 trials) preceded the experiment.
Data preprocessing and analysis

The same preprocessing procedures were applied as in Experiment 1. The proportion of trials with force exceeding pre-defined thresholds (±500 mN) ranged from 0% to 18% (mean = 2%), and no participant was excluded due to this criterion. Those trials were discarded. Accuracy varied from 97% to 100% (mean = 99%); error trials were excluded from further analysis.

Figure 9A represents averaged force of both hands for all accepted no-go trials plotted for words only. Independently of condition, grip force demonstrates the following pattern: there are two well-defined peaks of equal height (H130 and H350) with a slight deviation of force at the beginning of the second peak (H250). After H350, the force drops dramatically until 600 ms and remains relatively stable until the end of the epoch (1000 ms), with only a tiny wave having its peak at H850. Figure 9B represents averaged forces in go (dotted red line) and no-go (solid blue line) trials. These two lines start diverging at 230 ms after stimulus onset with force in go trials reaching its highest point (around 40 mN) at around 650 ms and remaining at this level till the end of the epoch. Figure 9C represents force averaged by condition (Hand X Word).

Fig. 9. Grip force changes (in milli-Newton) plotted against time from stimulus onset (in milliseconds), Experiment 3. Panel A. Averaged force profiles across all accepted no-go trials of all participants plotted for words. Panel B. Force profiles in go (dotted red line) and no-go (solid blue line) trials. These forces diverge around 230 ms after stimulus presentation. Panel C. Force profiles averaged by condition (Hand X Word). Yellow area (250-300 ms) indicates interaction between Hand and Word. Green area (880-970 ms) indicates the main effect of Hand (not significant). Red lines represent right-hand forces, blue lines – left-hand forces. Dotted lines represent the word-left condition, solid lines – word-center, dashed lines – word-right.

As before, a cluster permutation analysis with Hand and Word as within-variables and their interaction was used to identify time windows of interest. Five thousand permutations were performed, and TFCE (Threshold-Free Cluster Enhancement) correction for multiple comparisons was used. The analysis
revealed a main effect of Hand close to significance (880-970 ms) and two time windows with an interaction between Hand and Word close to significance (250-300 ms, see Figure 10, and 810-890 ms).

**Fig. 10. Grip force changes (in milli-Newton) averaged by Hand and Word in time widow 250300 ms, Experiment 3.** Whiskers represent standard errors.

**880-970 ms, Model 3.1.** As in Experiments 1 and 2, the data (averaged by Hand and Word for each participant) were then submitted to linear mixed model analysis. The categorical predictor Hand was sum-coded (left/right, sum-coded contrast -0.5 and 0.5). Word was re-coded in a continuous manner (left: -1; center: 0; right: 1). Interaction between Hand and Word was included. Participants were included as random factors. I performed a backward elimination using the drop1 function to identify the best-fit model; effects and interactions that did not improve model fit (p > .1) were successively eliminated. Only significant effects are reported unless the effect of interest in a given analysis was non-significant – in such cases, it is also reported.

No significant effects or interactions were revealed in this time window. The closest to significance was the main effect of Hand. The force was (non-significantly) lower in the left hand compared to the right hand (b = -3.355, p = .097). Marginal r-squared was .013, and conditional r-squared was .249. See Table 11 for further details.

**Table 11. Model 3.1.** Main effect of Hand on grip force in the time window 880-970 ms (not significant; Experiment 3).

| Random effects: | Name   | Variance | SD    |
|-----------------|--------|----------|-------|
| Participants    | Intercept | 52.2     | 7.225 |
| Residual        |         | 165.9    | 12.882|

| Fixed effects: | Intercept | b     | SE     | t-value | p-value |
|----------------|-----------|-------|--------|---------|---------|
|                |           | -7.866| 1.720  | 4.574   | .001    |
|                | Hand      | -3.355| 2.024  | -1.657  | .097    |

**250-300 ms, Models 3.2 and 3.3.** The same approach was used as for Experiment 1 (see time windows
60-130 ms and 260-1000 ms). Word was re-coded as a continuous variable (left: -1; center: 0; right: 1).

Each force was tested separately, with the contralateral force and Word as predictors. The effect of Word was significant in the left hand: the grip force increased for the word “right” compared to the word “left” (b = 1.736, p = .047; marginal r-squared = .171, conditional r-squared = .764; see Table 12), and in the right hand the force increased for the word “left” compared to the word “right” (b = 1.690, p = .041; marginal r-squared = .166, conditional r-squared = .768; see Table 13; see also Figure 11).

**Table 12. Model 3.2.** Effect of Direction on the left grip force (after controlling for the contralateral force) in the time window 250-300 ms (Experiment 3).

| Random effects: | Name | Variance | SD  |
|-----------------|------|----------|-----|
| Participants    | Intercept | 101.23 | 10.061 |
| Residual        | b    | 40.39 | 6.355 |

**Fixed effects:**

|                      | SE  | t-value | p-value |
|----------------------|-----|---------|---------|
| Intercept            | 2.061 | 1.339 | .180    |
| Contralateral hand   | 0.108 | 3.680 | < .001  |
| (right)              |      |         |         |
| Word                 | 1.736 | 0.875 | 1.983   | .047    |

**Table 13. Model 3.3.** Effect of Direction on the right grip force (after controlling for the contralateral force) in the time window 250-300 ms (Experiment 3).

| Random effects: | Name | Variance | SD  |
|-----------------|------|----------|-----|
| Participants    | Intercept | 94.34 | 9.713 |
| Residual        | b    | 36.25 | 6.021 |

**Fixed effects:**

|                      | SE  | t-value | p-value |
|----------------------|-----|---------|---------|
| Intercept            | 1.985 | 1.260 | .208    |
| Contralateral hand   | 0.098 | 3.648 | < .001  |
| (left)               |      |         |         |
| Word                 | -1.690 | 0.828 | -2.041 | .041    |
Fig. 11. Regression lines for the main effect of word semantics on force (Experiment 3, time window 250-300 ms). See main text for details (Models 3.2 and 3.3).

810-890 ms, Models 3.4 and 3.5. The same approach was used as for the previous time window. The effect of Word was not significant in the left hand ($b = 0.121$, $p = .938$; marginal r-squared = .210, conditional r-squared = .501; see Table 14), neither was it significant in the right hand ($b = 0.638$, $p = .619$; marginal r-squared = .188, conditional r-squared = .596; see Table 15).

Table 14. Model 3.4. Effect of Direction on the left grip force (after controlling for the contralateral force) in the time window 810-890 ms (Experiment 3).

| Random effects: | Name   | Variance | SD  |
|-----------------|--------|----------|-----|
| Participants    | Intercept | 75.94    | 8.715 |
| Residual        | $b$     | 130.15   | 11.408 |
| Fixed effects:  |        |          |      |
| Intercept       |        | 2.102    | -2.982 | .003 |
| Contralateral hand | (right) | 0.112    | 4.523 | < .001 |
| Word            |        | 0.121    | 1.555 | 0.078 | .938 |

Table 15. Model 3.5. Effect of Direction on the right grip force (after controlling for the contralateral force) in the time window 810-890 ms (Experiment 3).

| Random effects: | Name   | Variance | SD  |
|-----------------|--------|----------|-----|
| Participants    | Intercept | 89.61    | 9.466 |
| Residual        | $b$     | 88.60    | 9.413 |
| Fixed effects:  |        |          |      |
| Intercept       |        | 2.101    | -4.064 | < .001 |
| Contralateral hand | (left) | 0.086    | 4.762 | < .001 |
| Word            |        | 0.638    | 1.282 | 0.498 | .619 |

Thus, the effect of Word emerged at 250-300 ms, which is later than the effect of Position (Experiment 1) or Direction (Experiment 2). Moreover, the grip force increased in hand contralateral to the
expected one: in the right hand for the word “left” and in the left hand for the word “right”. This surprising finding will be discussed in detail in the last section.

Analysis at the individual level across experiments

Since the same individuals participated in all three experiments, it was possible to analyze data across studies. Note that this analysis is rather exploratory due to the small number of participants. I added random slopes to all models where significant interaction between Hand and Side (Position, Direction, or Word) emerged, for left and right hands separately: 60-130 ms and 260-1000 ms (Experiment 1), 100-150 ms (Experiment 2), and 250-300 ms (Experiment 3). These individual coefficients were submitted into a correlational analysis (see Table 16).

Table 16. Correlations between individual slopes across three experiments. Numbers in variable names denote time windows. S – stars (Experiment 1); A – arrows (Experiment 2); W – words (Experiment 3). LH – left-hand force; RH – right-hand force. N – number of participants included in the analysis (varied across experiments). *p < .05; **p < .01; ***p < .001.

|                | S 60-130 RH | S 260-1000 LH | S 260-1000 RH | A 100-150 LH | A 100-150 RH | W 250-300 LH | W 250-300 RH |
|----------------|-------------|---------------|---------------|--------------|--------------|--------------|--------------|
| N              | 41          | 41            | 41            | 40           | 40           | 26           | 26           |
| S 60-130 LH    | –.268       | –.013         | –.030         | –.300        | –.495**      | .250         | .174         | .090         | .300         | .495**       | .250         | .174         | .090         | .300         | .495**       | .250         | .174         | .090         | .300         |
|                | p = .853    | p = .061      | p = .001      | p = .218     | p = .394     | p = .001     | p = .001     | p = .001     | p = .001     | p = .001     | p = .001     | p = .001     | p = .001     | p = .001     | p = .001     | p = .001     | p = .001     | p = .001     |
| S 60-130 RH    | –.394*      | .625***       | .070          | .479**       | .257         | –            | –            | –            | –            | –            | –            | –            | –            | –            | –            | –            | –            | –            |
|                | .435* p = .111 | p < .001     | .0670         | .002         | p = .026     | p = .026     | p = .026     | p = .026     | p = .026     | p = .026     | p = .026     | p = .026     | p = .026     | p = .026     | p = .026     | p = .026     | p = .026     | p = .026     |
| S 260-1000 LH  | –.438**     | .147          | –.286         | –.510**      | .015 p = .004 | p = .366     | p = .074     | p = .008     | p = .944     | .253         | .174         | .230         | –.278        |
|                | p = .015    | p = .004      | p = .366      | p = .074     | p = .944     | p = .253     | p = .174     | p = .230     | p = .170     | p = .259     | p = .259     | p = .259     | p = .170     |
|                |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
|----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| A 100-150 LH   | – .402*| – .289 | – .111 | p = .010 | p = .152 | p = .591 | .197   | p = .336 | p = .388 | – .177   |
| A 100-150 RH   |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| W 250-300 LH   |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
| 480            |        |        |        |        |        |        |        |        |        |        |        |        |        |        |        |
Correlations between hands in the same time windows within the same experiments. A negative significant correlation \((r = – .438, p = .004)\) was found between the right-hand and left-hand coefficients in the time window 260-1000 ms (Experiment 1, star presentation). Since the effect of Side is oppositely directed in the left and right hands, this negative correlation demonstrates that both forces were influenced by the stimuli simultaneously at the individual level. In other words, the same participants, who demonstrated the effect in one hand, were also more likely to demonstrate it in another hand. The same pattern was found for the time window 100-150 ms in Experiment 2 (arrow presentation; \(r = – .402, p = .010)\). The correlation for the time window 60-130 ms in Experiment 1 (star presentation) was close to significance \((r = – .268, p = .090)\). The correlation for the time window 250-300 ms in Experiment 3 (word presentation) was also negative, though far from significance \((r = .217, p = .288)\). Overall, these results show that Position and Direction have simultaneous effects on both hands at the individual level. For Word, this cannot be concluded, perhaps due to absence of the effect or a smaller number of participants in Experiment 3 \((N = 26)\).

Correlations across time windows within the same experiment. More interesting is the positive correlation between right-hand slope coefficients for the time window 60-130 ms and 260-1000 ms (Experiment 1, star presentation; \(r = .625, p < .001)\). This correlation suggests that the effect of Position observed in the earlier time window (60-130 ms) and in the later one (260-1000 ms) is substantially the same effect that was interrupted between 130-260 ms, probably due to large force oscillations (H130 and L230, see Experiment 1). No such correlation was observed for the left-hand coefficients \((r = – .013, p = .936)\).

Correlations across experiments. Right-hand coefficients in the time window 60-130 ms, Experiment 1, correlated positively with right-hand coefficients in the time window 100-150 ms, Experiment 2 \((r = .479, p = .002)\). A negative correlation was observed for left-hand coefficients in the time window 60130 ms, Experiment 1, and right-hand coefficients in the time window 100-150 ms, Experiment 2 \((r = – .45, p = .001)\). These correlations demonstrate that the same participants, who showed the effect of
Position in Experiment 1 (star presentation), were more likely to exhibit a comparable effect of Direction in Experiment 2 (arrow presentation). More surprising are the other two negative correlations: the one between right-hand coefficients at 60-130 ms in Experiment 1 and at 250-300 ms in Experiment 3 ($r = -0.435, p = 0.026$); and the other one between left-hand coefficients at 260-1000 ms in Experiment 1 and at 250-300 ms at Experiment 3 ($r = -0.510, p = 0.008$). These two correlations indicate that the same participants who demonstrated the effect of Position in Experiment 1 (star presentation) also demonstrated the effect of Word in Experiment 3, although the effect of Word was the opposite of the expected.

In the next section, all results will be discussed in more detail.

**DISCUSSION**

The present study aimed to investigate the effects of spatial processing on the manual motor system by using a new method – bimanual grip force recording. In Experiment 1, participants’ visual attention was shifted using lateralized stimuli presentation (Experiment 1). In Experiment 2, participants were centrally presented with pictographic symbols with spatial meaning (left- or right-oriented arrows). In Experiment 3, participants were centrally presented with words having spatial meaning ("left" vs. "right"). Since a go/no-go paradigm with a verbal response in go trials was used, any observed effects can only be attributed to spatial/semantic processing alone and not to motor preparation of responses.

*General pattern of grip force changes.* The first important finding is that all three types of stimuli (stars, arrows, and words) led to very similar initial force patterns (see Figure 12), namely two peaks (around 130 and 300-350 ms after stimulus onset) followed by differentially declining force profiles. I will now interpret these results in turn.

**Figure 12. Averaged forces from both hands across all no-go trials (regardless of condition) in three experiments.** The dotted pink line represents force modulations caused by the presentation of stars (Experiment 1), dashed green line – arrows (Experiment 2), solid orange line – words
(Experiment 3). Colored horizontal bars in the lower part of the graph represent time windows with significant Side X Hand interactions for all three types of stimuli – stars, arrows, and words. The colors of bars correspond to the colors of lines described above.

This pattern is very close to force profiles observed in studies with other stimuli – numbers (15) and human faces (Miklashevsky et al., in prep.). In response to numbers, grip force peaked at 100 ms and later at 350 ms. Two more prominent peaks (around 100-130 and 300-350 ms) probably reflect two processing stages: (1) initial processing of any stimulus appearing on a screen and (2) decision-making or response inhibition process accordingly. Remember that only no-go trials are included in analyses. The divergence point between forces (230-250 ms) in go and no-go trials always precedes the second peak – i.e., at this point, participants’ arousal increases in trials requiring response and should be inhibited in trials where no response is needed. These assumptions require confirmation in future studies.

Interestingly, a slight deviation formed an additional peak at 250 ms in an earlier study with numbers (15) which results in a pattern very similar to those observed for words and (less pronounced) arrows in the present study but not for stars (in this study) or faces (in a previous study, unpublished). Since numbers, words, and arrows are all symbolic stimuli, I hypothesize that this smaller peak around 250 ms reflects some process specific to the understanding of symbols.

Suppose my hypothesis is correct and grip force reflects not only motor-related but also more general cognitive processes, such as stimulus identification and preparation or inhibition of verbal responses. In that case, this has implications for other studies using the force registration method. In previous studies of this kind (e.g., 19,21), force changes were always interpreted as specific signatures of activity in the manual motor system. However, a recent study shows that even observing foot actions leads to changes in grip force (30), perhaps due to automatic propagation of activity in the motor brain areas. The same principle might be at play in the present study. Thus, it might be methodologically
incorrect to choose force at the time point of stimulus onset as a baseline and compare different conditions with it since any stimulus might lead to force oscillations. Different conditions should be compared with each other instead, or a continuous coding of variables should be chosen as in the present study.

*Influence of spatial processing on grip force changes.* Regarding the specific hypothesis of the present study, i.e., whether or not spatial attentional shifts lead to the automatic activation of the manual motor system – the answer is yes, although with some reservations. When lateralized stimuli appeared (stars, Experiment 1), a significant difference in force emerged already at 60-130 ms and later at 260-1000 ms. The force increased larger in each of the hands when the star was presented on the ipsilateral side; this increase was smaller for stars presented on the contralateral side. This effect was stronger in the right hand in both time windows. Since individual linear coefficients for both time windows (60-130 ms and 260-1000 ms) correlated positively for the right hand, I suppose these two time windows reflect the same effect. The interruption between the two windows appears due to the multiphasic structure of force profiles: forces in all conditions go down rapidly between 130 and 230 ms, thus reducing differences between conditions. Note that no significant effects were found in all three experiments in this time interval.

A similar pattern, although less pronounced, appeared for arrows (Experiment 2): the force increased larger in each of the hands for arrows pointing in that hand’s direction; the increase was smaller for arrows pointing in the opposite direction. This effect emerged later than (at 100 ms), lasted shorter (just 50 ms), and was weaker than for stars. Nevertheless, it was also found in the first "wave" (H130), i.e., it probably belongs to the same processing stage. It is not surprising since symbolic cues have a similar impact on attention as physical ones, even if these symbolic cues are task-irrelevant (see 52,53). The present study provides even more substantial evidence in favor of the automatic effect of arrows on the attentional system than the studies by Hommel, Pratt et al. (52), or Ranzini et al. (53). In these previous studies, the arrows themselves were non-predictive, but lateralized stimuli still followed arrows. In the present study, no lateralized stimuli were used (Experiment 2), yet force patterns
resembled those produced by exogenous attentional shifts. The effect for arrows (Experiment 2),
measured as regression coefficients, correlated with the effect for stars (Experiment 1) at the individual
level, indicating stable inter-individual differences in motor response to spatial stimuli.

Arrows are viewed as symbolic stimuli in the present study, although there is a debate about their
actual status: arrows demonstrate effects typical for both exogenous and endogenous cues. Ristic and
Kingstone even speak of the third form of attention – automated symbolic orienting (34). In the present
study, the general force pattern for arrows is similar to both: the pattern produced by words (the
second peak, H300, is lower than the first one, H130), but also to the pattern produced by stars (grip
force does not drop as deeply as for words after 300-350 ms and there is a slight increase around 600-
650 ms). The same is true regarding the effect of spatial information: qualitatively similar to those
produced by stars, it is at the same time weaker for arrows. It appears later than for stars but earlier
than for words.

A significant effect of word semantics on force was found in Experiment 3. Yet, the direction of this
effect was surprising: the force increased more for words related to the opposite side; this increase was
smaller for words related to the same side. The effect appeared rather late (250-300 ms) and was of
comparable strength across both hands. Note that it belongs to the second larger force wave and
emerges simultaneously with the tiny force deviation discussed above (H250). This information might
be crucial for interpreting the direction of the effect: remember that participants inhibited their verbal
response in no-go trials, and the divergence point between go and no-go trials, presumably reflecting
the moment of such inhibition, was exactly 230 ms. The stronger H250 wave probably results from the
conflict between the two overlapping processes: automatic activation of word semantics and conscious
inhibition of verbal response. By suppressing semantics of the word “left”, participants literally had to
inhibit activity in the left hand (for more details on the interplay between the semantic and motor
system see the HANDLE model, 54); the same happened with the word “right” and the right hand. To
further examine this hypothesis, it would be necessary to design a study following the procedure of
Experiment 3 but with a non-linguistic response. I predict that words will exhibit force patterns similar to those in Experiments 1 and 2 in such a study since no inhibition of motor semantics should happen. If this is the case, this finding has implications for the research on inhibitory control: multiple measures of this presumably higher-order construct often do not correlate with each other (e.g., 55). The reason might be that inhibitory control does not constitute a single construct but is instead highly domain-specific.

The findings of the present study are in line with neuroscientific research of attention. ERP research established a fine-graded time course of attentional processes. Attentional effects on the processing of lateralized stimuli were found in the magnitude of P1 (60-100 ms after stimulus onset), N1 (around 150 ms), and P2 (around 200 ms) ERP components (see for review 56). Effects of symbolic control of attention induced by using centrally presented arrows appear at 200-400 ms after cue onset over contralateral posterior sites (the so-called early directing attention negativity, EDAN), probably reflecting encoding spatial information provided by the cue. EDAN follows by anterior directing attention negativity (ADAN) appearing over contralateral anterior sites at 300-500 ms and performing attentional shift. Finally, a positive waveform (late directing attention positivity, LDAP) appears after 500 ms after cue onset and presumably represents top-down modulation in the excitability of sensory areas (also 53, see for review 57). This observation aligns with reaction time research demonstrating the highest performance in detecting targets around 300 ms after the onset of a symbolic cue. Still, this effect appears even earlier (see 58, for discussion). The present study confirms very early effects of both lateralized visual stimuli (60-130 ms) and centrally presented symbolic cues (100-150 ms). It also demonstrates that these effects are detectable in the manual motor system. Such early and automatic modulation is one of the signatures of functional coupling between two structures and not mere spreading spillover activation (see 59).

Although the present study shares many similarities with classical research using the Posner paradigm, substantial differences in the setup and procedure should be considered when comparing the current
results with previous studies. First, no laterally appearing stars, arrows, or words were cues in the original sense of this term: there were no "target" stimuli following them. Instead, they were themselves the targets. While lateralized stars indeed led to automatic attentional shifts due to their location, symbolic cues (arrows and words) could indirectly shift attention, following automatic processing of their meaning, which was not necessary for the color discrimination task. The task itself required merely superficial processing (60) and was not related to spatial information. These factors taken together make the similarity between effects of lateralized stimuli and centrally presented arrows even more remarkable. Further research should vary the role of stimuli (by turning them into cues with varying validity as in the original Posner paradigm) and complexity of the motor task to clarify the exact functional relationship between the attentional and manual motor systems (cf. 61).

Conclusion

The present study investigated the relationship between spatial attention and the manual motor system by using a go/no-go paradigm and bimanual registration of grip force. Automatic and rapid changes in grip force were found in response to lateralized visual stimuli (Experiment 1) and centrally presented symbolic stimuli (Experiments 2, arrows, and 3, words). This activity followed a similar early biphasic pattern for all kinds of stimuli: one peak emerged at 130 ms and another at 300-350 ms after stimulus onset. For both lateralized objects and centrally presented arrows, the direction of the effect was as predicted, i.e., the left force increased in response to objects presented on the left side or left-pointing arrows, while the opposite was true for the right force. This effect appeared very early for lateralized objects (60 ms) and slightly later for arrows (100 ms). A reverse pattern was observed for words: each of the two forces increased for words related to the opposite side. The effect for words was significant at 250-300 ms after stimulus onset. This surprising finding might indicate an interaction between automatic semantic activation and inhibition of verbal responses required in no-go trials. Overall, the results suggest a close relationship between attentional processes and the manual motor system. Further research should clarify the functional role of the manual motor system activation in processing spatial information.
Acknowledgments

I thank Martin H. Fischer for his valuable feedback on the early versions of this manuscript. I acknowledge the support of the Deutsche Forschungsgemeinschaft (DFG) and Open Access Publishing Fund of the University of Potsdam.

Data Availability Statement

The datasets generated for this study can be found in the Open Science Framework (OSF) at https://doi.org/10.17605/OSF.IO/H6P7M.

References

1. Rizzo J-R, Hosseini M, Wong EA, Mackey WE, Fung JK, Ahdoot E, et al. The Intersection between Ocular and Manual Motor Control: Eye–Hand Coordination in Acquired Brain Injury. Front Neurol. 2017 Jun 1;8:227.

2. Baldauf D, Wolf M, Deubel H. Deployment of visual attention before sequences of goal-directed hand movements. Vision Res. 2006 Dec;46(26):4355–74.

3. Baldauf D, Deubel H. Visual attention during the preparation of bimanual movements. Vision Res. 2008 Feb;48(4):549–63.

4. Festman Y, Adam JJ, Pratt J, Fischer MH. Continuous hand movement induces a far-hand bias in attentional priority. Atten Percept Psychophys. 2013 May;75(4):644–9.

5. Chapman CS, Gallivan JP, Wood DK, Milne JL, Culham JC, Goodale MA. Reaching for the unknown: Multiple target encoding and real-time decision-making in a rapid reach task. Cognition. 2010 Aug;116(2):168–76.

6. Gallivan JP, Chapman CS. Three-dimensional reach trajectories as a probe of real-time decisionmaking between multiple competing targets. Front Neurosci [Internet]. 2014 Jul 23 [cited 2020 Sep 3];8. Available from: http://journal.frontiersin.org/article/10.3389/fnins.2014.00215/abstract

7. Hommel B, Chapman CS, Cisek P, Neyedli HF, Song J-H, Welsh TN. No one knows what attention is. Atten Percept Psychophys. 2019 Oct;81(7):2288–303.

8. Abrams RA, Davoli CC, Du F, Knapp WH, Paull D. Altered vision near the hands. Cognition. 2008 Jun;107(3):1035–47.

9. Davoli CC, Brockmole JR. The hands shield attention from visual interference. Atten Percept Psychophys. 2012 Oct;74(7):1386–90.

10. Reed CL, Grubb JD, Steele C. Hands up: Attentional prioritization of space near the hand. J Exp Psychol Hum Percept Perform. 2006;32(1):166–77.
11. Brockmole JR, Davoli CC, Abrams RA, Witt JK. The World Within Reach: Effects of Hand Posture and Tool Use on Visual Cognition. Curr Dir Psychol Sci. 2013 Feb;22(1):38–44.

12. Adam JJ, Bovend’Eerdt TJH, van Dooren FEP, Fischer MH, Pratt J. The closer the better: Hand proximity dynamically affects letter recognition accuracy. Atten Percept Psychophys. 2012 Oct;74(7):1533–8.

13. Davoli CC, Du F, Montana J, Garverick S, Abrams RA. When meaning matters, look but don’t touch: The effects of posture on reading. Mem Cognit. 2010 Jul;38(5):555–62.

14. Davoli CC, O’Rear CD, McAulay E, McNeil NM, Brockmole JR. Hand position affects performance on multiplication tasks. J Numer Cogn. 2020 Jun 15;6(1):1–21.

15. Miklashevsky A, Lindemann O, Fischer MH. The Force of Numbers: Investigating Manual Signatures of Embodied Number Processing. Front Hum Neurosci. 2021 Jan 11;14:590508.

16. Aravena P, Delevoye-Turrell Y, Deprez V, Cheylus A, Paulignan Y, Frak V, et al. Grip Force Reveals the Context Sensitivity of Language-Induced Motor Activity during “Action Words” Processing: Evidence from Sentential Negation. PLOS ONE. 2012 Dec 5;7(12):e50287.

17. Aravena P, Courson M, Frak V, Cheylus A, Paulignan Y, Deprez V, et al. Action relevance in linguistic context drives word-induced motor activity. Front Hum Neurosci [Internet]. 2014 [cited 2020 Jun 22];8. Available from: https://www.frontiersin.org/articles/10.3389/fnhum.2014.00163/full

18. da Silva RL, Santos FF, Mendes IMG, Caromano FA, Higgins J, Frak V. Contributions of the Left and the Right Hemispheres on Language-Induced Grip Force Modulation of the Left Hand in Unimanual Tasks. Medicina (Mex). 2019 Oct 6;55(10):674.

19. Frak V, Nazir T, Goyette M, Cohen H, Jeannerod M. Grip force is part of the semantic representation of manual action verbs. PloS One. 2010 Mar 16;5(3):e9728.

20. Pérez-Gay Juárez F, Labrecque D, Frak V. Assessing language-induced motor activity through Event Related Potentials and the Grip Force Sensor, an exploratory study. Brain Cogn. 2019 Oct 1;135:103572.

21. Nazir TA, Hrycyk L, Moreau Q, Frak V, Cheylus A, Ott L, et al. A simple technique to study embodied language processes: the grip force sensor. Behav Res Methods. 2017 Feb 1;49(1):61–73.

22. Dehaene S, Bossini S, Giraux P. The mental representation of parity and number magnitude. J Exp Psychol Gen. 1993;122(3):371–96.

23. Fischer MH. Spatial representations in number processing—evidence from a pointing task. Vis Cogn. 2003 May 1;10(4):493–508.

24. Myachykov A, Ellis R, Cangelosi A, Fischer MH. Ocular drift along the mental number line. Psychol Res. 2016 May 1;80(3):379–88.

25. Schwarz W, Müller D. Spatial Associations in Number-Related Tasks. Exp Psychol. 2006 Jan 1;53(1):4–15.
26. Fischer MH, Shaki S. Spatial Associations in Numerical Cognition—From Single Digits to Arithmetic. Q J Exp Psychol. 2014 Aug 1;67(8):1461–83.

27. Toomarian EY, Hubbard EM. On the genesis of spatial-numerical associations: Evolutionary and cultural factors co-construct the mental number line. Neurosci Biobehav Rev. 2018 Jul 1;90:184–99.

28. Wood G, Willmes K, Nuerk H-C, Fischer MH. On the cognitive link between space and number: A meta-analysis of the SNARC effect. Psychol Sci. 2008;50(4):489–525.

29. Shaki S, Fischer MH. Deconstructing spatial-numerical associations. Cognition. 2018 Jun 1;175:109–13.

30. Blampain J, Ott L, Delevoye-Turrell YN. Seeing action simulation as it unfolds: The implicit effects of action scenes on muscle contraction evidenced through the use of a grip-force sensor. Neuropsychologia. 2018 Jun 1;114:231–42.

31. da Silva RL, Labrecque D, Caromano FA, Higgins J, Frak V. Manual action verbs modulate the grip force of each hand in unimanual or symmetrical bimanual tasks. PLoS ONE [Internet]. 2018 Feb 5 [cited 2020 Apr 13];13(2). Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5798821/

32. Klein RM. On the Control of Visual Orienting. In: Cognitive neuroscience of attention. New York, NY, US: The Guilford Press; 2004. p. 29–44.

33. Posner MI. Orienting of attention. Q J Exp Psychol. 1980 Feb;32(1):3–25.

34. Ristic J, Kingstone A. A new form of human spatial attention: Automated symbolic orienting. Vis Cogn. 2012 Mar;20(3):244–64.

35. Dudschig C, Lachmair M, de la Vega I, De Filippis M, Kaup B. From top to bottom: spatial shifts of attention caused by linguistic stimuli. Cogn Process. 2012 Aug;13 Suppl 1:S151-154.

36. Dudschig C, Souman J, Lachmair M, Vega I de la, Kaup B. Reading “Sun” and Looking Up: The Influence of Language on Saccadic Eye Movements in the Vertical Dimension. Lappe M, editor. PLoS ONE. 2013 Feb 27;8(2):e56872.

37. Estes Z, Verges M, Barsalou LW. Head up, foot down: object words orient attention to the objects’ typical location. Psychol Sci. 2008 Feb;19(2):93–7.

38. Chasteen AL, Burdzy DC, Pratt J. Thinking of God moves attention. Neuropsychologia. 2010 Jan;48(2):627–30.

39. Janyan A, Vankov I, Tsaregorodtseva O, Miklashevsky A. Remember down, look down, read up: Does a word modulate eye trajectory away from remembered location? Cogn Process. 2015 Sep;16(S1):259–63.

40. Oldfield RC. The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia. 1971 Mar 1;9(1):97–113.

41. Robinson J. Edinburgh Handedness Inventory. In: Volkmar FR, editor. Encyclopedia of Autism Spectrum Disorders [Internet]. New York, NY: Springer; 2013 [cited 2020 Aug 1]. p. 1051–4. Available from: https://doi.org/10.1007/978-1-4419-1698-3_877
42. Mathôt S, Schreij D, Theeuwes J. OpenSesame: An open-source, graphical experiment builder for the social sciences. Behav Res Methods. 2012 Jun 1;44(2):314–24.

43. Krause F, Lindemann O. Expyriment: A Python library for cognitive and neuroscientific experiments. Behav Res Methods. 2014 Jun 1;46(2):416–28.

44. R Core Team. R: A language and environment for statistical computing. In: R Foundation for Statistical Computing [Internet]. Vienna, Austria; 2020 [cited 2020 Jun 23]. Available from: https://www.R-project.org/

45. Frossard J, Renaud O. Permutation tests for regression, ANOVA and comparison of signals: the permuco package. 2018;27.

46. Bates D, Mächler M, Bolker B, Walker S. Fitting Linear Mixed-Effects Models Using lme4. J Stat Softw [Internet]. 2015 [cited 2020 Dec 29];67(1). Available from: http://www.jstatsoft.org/v67/i01/

47. Barr DJ, Levy R, Scheepers C, Tily HJ. Random effects structure for confirmatory hypothesis testing: Keep it maximal. J Mem Lang. 2013 Apr 1;68(3):255–78.

48. Nakagawa S, Schielzeth H. A general and simple method for obtaining $R^2$ from generalized linear mixed-effects models. O’Hara RB, editor. Methods Ecol Evol. 2013 Feb;4(2):133–42.

49. Mathew J, de Rugy A, Danion FR. How optimal is bimanual tracking? The key role of hand coordination in space. J Neurophysiol. 2020 Feb 1;123(2):511–21.

50. Friesen CK, Ristic J, Kingstone A. Attentional Effects of Counterpredictive Gaze and Arrow Cues. J Exp Psychol Hum Percept Perform. 2004;30(2):319–29.

51. Marotta A, Román-Caballero R, Lupiáñez J. Arrows don’t look at you: Qualitatively different attentional mechanisms triggered by gaze and arrows. Psychon Bull Rev. 2018 Dec;25(6):2254–9.

52. Hommel B, Pratt J, Colzato L, Godijn R. Symbolic Control of Visual Attention. Psychol Sci. 2001 Sep;12(5):360–5.

53. Ranzini M, Dehaene S, Piazza M, Hubbard EM. Neural mechanisms of attentional shifts due to irrelevant spatial and numerical cues. Neuropsychologia. 2009 Oct;47(12):2615–24.

54. García AM, Ibáñez A. A touch with words: Dynamic synergies between manual actions and language. Neurosci Biobehav Rev. 2016 Sep;68:59–95.

55. Gärtner A, Strobel A. Individual Differences in Inhibitory Control: A latent Variable Analysis. J Cogn. 2021 Feb 18;4(1):17.

56. Luck SJ, Woodman GF, Vogel EK. Event-related potential studies of attention. Trends Cogn Sci. 2000 Nov;4(11):432–40.

57. Eimer M, Velzen J van, Driver J. Cross-Modal Interactions between Audition, Touch, and Vision in Endogenous Spatial Attention: ERP Evidence on Preparatory States and Sensory Modulations. J Cogn Neurosci. 2002 Feb 1;14(2):254–71.
58. Klein RM. Is covert spatial orienting embodied or disembodied cognition? A historical review. Q J Exp Psychol. 2020 Jan;73(1):20–8.

59. Pulvermüller F. Meaning and the brain: The neurosemantics of referential, interactive, and combinatorial knowledge. J Neurolinguistics. 2012 Sep 1;25(5):423–59.

60. Craik FIM, Lockhart RS. Levels of processing: A framework for memory research. J Verbal Learn Verbal Behav. 1972 Dec;11(6):671–84.

61. Ibáñez A, García AM. Context as Inter-domain Effects: The Hand-Action-Network Dynamic Language Embodiment Model. In: Ibáñez A, García AM, editors. Contextual Cognition: The Sensus Communis of a Situated Mind [Internet]. Cham: Springer International Publishing; 2018
Figure captions

**Fig. 1. Experimental setup and equipment.** Panel A. Bimanual force recording setup. Panel B. Grip
force sensor (X – longitudinal, Y – radial, Z – compression forces). C. The way participants held
the sensors (around 45° relative to the table surface, not strictly controlled). Adapted image from Miklashevsky et al. (15, Fig. 2).

**Fig. 2. Grip force changes (in milli-Newton) plotted against time from stimulus onset (in milliseconds), Experiment 1.** Panel A. Averaged force profiles across all accepted no-go trials of all participants. Panel B. Force profiles in go (dotted red line) and no-go (solid blue line) trials. These forces diverge around 250 ms after stimulus presentation. Panel C. Force profiles averaged by condition (Hand X Position). Light-yellow areas (60-130 ms and 260-1000 ms) indicate interactions between Hand and Position, green area (820-1000 ms) indicates the main effect of Hand. Red lines represent right-hand forces, blue lines – left-hand forces. Dotted lines represent the star-left condition, solid lines – star-in-the-center condition, dashed lines – star-right condition.

**Fig. 3. Grip force changes (in milli-Newton) averaged by Hand and Position, Experiment 1.** Panel
A. Average forces in time widow 60-130 ms. Panel B. Average forces in time widow 260-1000 ms.
Whiskers represent standard errors.
Fig. 4. Regression lines for the main effect of star position on force (Experiment 1, time window 60-130 ms). See main text for details (Models 1.3 and 1.4).
Fig. 5. Regression lines for the main effect of star position on force (Experiment 1, time window 260-1000 ms). See main text for details (Models 1.5 and 1.6).

Fig. 6. Grip force changes (in milli-Newton) plotted against time from stimulus onset (in milliseconds), Experiment 2. Panel A. Averaged force profiles across all accepted no-go trials of all participants. Panel B. Force profiles in go (dotted red line) and no-go (solid blue line) trials. These forces diverge around 250 ms after stimulus presentation. Panel C. Force profiles averaged by condition (Hand X Direction). Yellow area (100-150 ms) indicates interaction between Hand and Direction; violet area (620-800 ms) represents the main effect of Direction close to significance (p < .1). Red lines represent right-hand forces, blue lines – left-hand forces. Dotted lines represent the arrow-left condition, solid lines – arrow-in-both-directions, dashed lines – arrow-right.

Fig. 7. Grip force changes (in milli-Newton) averaged by Hand and Direction in time window 100-150 ms, Experiment 2. Whiskers represent standard errors.

Fig. 8. Regression lines for the main effect of arrow direction on force (Experiment 2, time window 100-150 ms). See main text for details (Models 2.3 and 2.4).

Fig. 9. Grip force changes (in milli-Newton) plotted against time from stimulus onset (in milliseconds), Experiment 3. Panel A. Averaged force profiles across all accepted no-go trials of all participants plotted for words. Panel B. Force profiles in go (dotted red line) and no-go (solid blue line) trials. These forces diverge around 230 ms after stimulus presentation. Panel C. Force profiles averaged by condition (Hand X Word). Yellow area (250-300 ms) indicates interaction between Hand
and Word. Green area (880-970 ms) indicates the main effect of Hand (not significant). Red lines represent right-hand forces, blue lines – left-hand forces. Dotted lines represent the word-left condition, solid lines – word-center, dashed lines – word-right.

**Fig. 10.** Grip force changes (in milli-Newton) averaged by Hand and Word in time widow 250-300 ms, Experiment 3. Whiskers represent standard errors.

**Fig. 11.** Regression lines for the main effect of word semantics on force (Experiment 3, time window 250-300 ms). See main text for details (Models 3.2 and 3.3).

**Figure 12.** Averaged forces from both hands across all no-go trials (regardless of condition) in three experiments. The dotted pink line represents force modulations caused by the presentation of stars (Experiment 1), dashed green line – arrows (Experiment 2), solid orange line – words (Experiment 3). Colored horizontal bars in the lower part of the graph represent time windows with significant Side X Hand interactions for all three types of stimuli – stars, arrows, and words. The colors of bars correspond to the colors of lines described above.
Figure 4

Click here to access/download;Figure;Fig.3.ti
Figure 7

Left hand

Right hand

Force change (mN)

star left  star center  star right

star left  star center  star right
Click here to access/download; Figure; Fig. 6.tif
Figure 12

Left hand

Right hand

Force change (mN)

arrow left  arrow center  arrow right

arrow left  arrow center  arrow right
Figure 15

Figure 10.tif

250-300 ms

Grip force change (mN)

Word left: Right hand 4.0 ± 0.5, Left hand 2.5 ± 0.3
Word center: Right hand 4.5 ± 0.7, Left hand 3.2 ± 0.4
Word right: Right hand 3.8 ± 0.6, Left hand 2.9 ± 0.3
Figure 17

This figure shows the force change (mN) for left and right hands with words placed on the left, center, and right. The left hand shows an increasing trend with word position, while the right hand shows a decreasing trend.
Reviewer #1 – authors’ comments analysis:

REVIEW – Catch the star! Spatial information activates the manual motor system

The study aims to evaluate the relationship between the manual motor system and exogenous and endogenous attention, the latter associated with two different forms of processing.

It is a very interesting manuscript, well written, addressing a relevant subject, and seeking evidence of important connections between motor function, central processing of sensory and motor information and attentional response. I only have a few considerations about it, described below by section.

Introduction

The introduction was very well organized, presenting the theoretical framework in a structured and direct manner. The citations are current and relevant, properly building the line of reasoning that culminates in the presentation of the objective of the study. The reasons for investigating the relationship of the manual motor system with endogenous attention through two experiments, however, were not presented, causing a break in the development of the introduction. In this sense, lines 339-345 should be part of the introduction to justify the decision to carry out two experiments involving endogenous attention.

I shifted lines 339-345 to the introduction.

R1 – Ok.

Methods and Results

The decision to present each experiment individually facilitates understanding. However, some aspects of the Methods that are valid for two or three experiments could be grouped together at the beginning of this section or presented in a single Table to allow a better visualization of the details of each experiment, e.g. exclusion of participants, exclusion of trials, accuracy, 5000 permutations performed in the cluster permutation analysis. There is no reason to describe the dips as they will not be discussed at any time. If you believe that these data are particularly important, Figures 2, 5, and 7 can present them satisfactorily, thus bringing more fluidity to the reading of the text.

Thank you for these suggestions. I already described most details relevant for all three experiments in the General Method section. Since exclusion of trials or the number of permutations require deeper explanations of the method (force thresholds and cluster permutation analysis), I decided to provide this information in smaller portions in a narrative manner. I believe this will facilitate understanding for readers who are not familiar with these methods.
Following your suggestion, I removed information about force dips from the text.

R1 – Ok.

The supplementary material brings the images of the stars and arrows as they were presented to the participants. However, there is no image for experiment 3. I was not able to open the words.osexp file, and the manuscript text does not provide information regarding the font, serif, and word style.

*Opening .osexp-files requires OpenSesame [https://osdoc.cogsci.nl] to be installed.* I added this information to the supplementary file on OSF. I also added detailed information about font to the manuscript: “Participants saw words or stimuli symbol arrays having a length of around 2.5 cm (2.39 degrees of visual angle) in a 25 px (19 pt) Droid Sans Mono font.” (line 392).

R1 – Ok.

Furthermore, in experiments 1 and 2, the stimuli were presented in two colors, one of which was associated with the verbal task. However, in experiment 3, in addition to colors, there are two types of text (words and symbols). Thus, the data sample for each condition dropped from 90 in experiments 1 and 2 to 60 in experiment 3, the same experiment that had a 35% drop in sample size. What is the point of introducing symbols arrays in Experiment 3, in red and yellow, if these constructions did not contribute to the discussion and were not statistically analyzed?

The original motivation for adding symbol arrays was to control for potential lexicality effects (cf. in EEG research: [https://doi.org/10.1016/j.bandl.2008.12.001]). I.e., it was possible that words lead to a specific pattern of grip force, and introducing non-word stimuli would then reveal word-specific force oscillations. However, it was not the case: all stimuli resulted in a similar force pattern. While I performed additional analysis for non-word stimuli, it did not help interpret the results related to the main hypothesis of the study. Thus, I decided not to include these distracting details in the manuscript.

Even though the data sample dropped to 60 trials per condition in Experiment 3, this number is still much larger than those used in previous force registration studies (e.g., [https://doi.org/10.1371/journal.pone.0050287]). Moreover, unlike linguistic studies with varying words and sentences, the present study repeated just three stimuli of interest (“left”, “center”, and “right”), which should additionally reduce variability of the dependent measure.

R1 – Although you have decided not to include the no-word stimuli results in the manuscript, you have decided to include its description. There is no problem about not having a hypothesis validated by the results, but it is not interesting that the data are not presented because they do not agree with that given hypothesis. I suggest exposing such data and discussing this topic in the manuscript - the hypothesis, the results, and their implication in the study - or removing this detail from the description of the experiment.
In addition, the sample has participants with different levels of consistency in manuality. Did this feature have no impact on the results? Especially in relation to experiment 3, due to its smaller sample, what was the impact of the sample low consistency in manuality? What was the behavior of the left-handed portion of the sample regarding the results obtained? Wouldn’t removing these participants from the sample imply more consistent results?

I performed an exploratory analysis with and without a left-handed subsample, but there were no qualitative changes in the results. Due to the small size of the left-handed subsample (N = 4) it was not meaningful to analyze their data separately.

R1 – Ok.

At various times, you classify your findings as close to significance. This is especially noteworthy in experiment 2, when a result close to significance reached p=.1. What is the threshold for considering a result close to or far from significance? Would considering these values as not significant significantly change your results? I believe that the text needs to be better worked on this point.

For the mixed linear modeling method, I used a significance threshold of p = .1 to keep the variables in the model (cf. the recommendations in https://doi.org/10.1016/j.bandl.2021.104941), while always explicitly mentioning such effects as “close to significance” in the text. The only threshold qualifying effects to be significant was the standard of p = .05.

Considering “close to significance” values as insignificant would not substantially change the results of the study. The main effects of Position (Model 1.3), Direction (Models 2.1 and 2.2), or Hand (Model 3.1) that were close to significance are of less interest for the main hypothesis. Moreover, effects of Position and Direction have different signs for different hands, as further detailed analysis shows; averaging them thus necessarily reduces the overall level of significance. Most critical for the research hypothesis are effects found in each hand separately, such as in Model 1.4. Among those, there was only one effect with a p-value above the standard significance level (effect of star position in the left hand at 60-130 ms, Model 1.3; p = .052). In this case, however, the effect of Position was significant in the right hand in the same time window (p = .005). Also, it became significant in the left hand in the following time window of 260100 ms (p = .011), with the same qualitative pattern. This converging evidence indicates that the effect was already present in the left hand at 60-130 ms and thus should be interpreted as real and not just a statistical artifact.

R1 – Ok.
Although you present the conditional r and the marginal r of each calculation and experiment, you do not comment on the relative value of their different values throughout the study. Could you comment more on this?

I explained these values when describing Model 1.1: “Marginal r-squared (variance explained by fixed effects, see Nakagawa & Schielzeth, 2013) was .041, and conditional r-squared (variance explained by the whole model, i.e., fixed and random effects together) was .451.”

R1 – Ok.

Discussion
In the discussion, you say that the force increased for one hand and decreased for the other, as per the experiment. However, in the graphs, it is not possible to observe a drop in force in relation to the moments prior to the peak force zone, that is, there is not a valley and a peak occurring simultaneously when observing the tracing for each hand in Figures 2C and 5C. Figure 7C is quite confusing as to the line of each condition in the interaction between Hand and Word area.

Is there really a drop in the force exerted by the contralateral hand in experiments 1 and 2 and by the ipsilateral hand in experiment 3? Is it not possible that the increase in force is simply happening later, as appears to be represented in Figure 7C? Please explain more about this.

Thank you for pointing out this invalid formulation. Indeed, while I referred to the results from linear modeling, it would be more appropriate to talk here about absolute values. The force always increases regardless of the condition, as the general pattern for each experiment demonstrates (Figures 2A, 5A, and 7A). I meant here (also corrected in the manuscript on page 29):

“The force increased larger in each of the hands when the star was presented on the ipsilaterial side; this increase was smaller for stars presented on the contralateral side.”

The corresponding correction has also been made regarding the other two experiments (pp. 29-30).

R1 – Ok.

Similarly, the hypothesis regarding the grip force increasing of the contralateral hand in experiment 3 lacks further detail. The text seeks to explain that the inhibitory stimulus for the execution of the movement of the ipsilateral hand has a more pronounced effect in experiment 3 due to a greater semantic processing. However, what would lead to an increase of the grip force of the contralateral hand? Or is this increase just relative? I believe this is the most awaited part of the discussion, and, as it stands, it is not at the level of the work performed with so much labor and perfection described in this manuscript.

Indeed, as I stated above, this was an unfortunate expression: there is no decrease but a relative increase in all cases. I interpreted this surprising finding
as a conflict between word semantics and required vocal response: “The stronger H250 wave probably results from the conflict between the two overlapping processes: automatic activation of word semantics and conscious inhibition of verbal response. By suppressing semantics of the word “left”, participants literally had to inhibit activity in the left hand (for more details on the interplay between the semantic and motor system, see the HANDLE model, 54); the same happened with the word “right” and the right hand.”

Note that I added a reference to the work by García and Ibáñez (2016) where they discuss differing directions of the motor effects in embodied cognition research, depending on the timing, motor, and linguistic demands. Nevertheless, at this point, this is just a hypothetical post-hoc explanation since there are not enough studies using grip force registration in numerical cognition research. That is why I added the following suggestion to the General Discussion (p. 30):

“To further examine this hypothesis, it would be necessary to design a study following the procedure of Experiment 3 but with a non-linguistic response. I predict that words will exhibit force patterns similar to those in Experiments 1 and 2 in such a study since no inhibition of motor semantics should happen.”

R1 – Ok.

Figures
In the text, the caption of figure 7 states that the interaction area between Hand and Word occurs between 830-860 ms, but, from the figure, I believe it occurs between 230-260 ms.

Thank you for pointing this out. It should be 250-300 ms. I corrected the caption.

R1 – Ok.

The Figures 2C, 5C and 7C are very important to the manuscript and deserve a better treatment. The color code used for the interaction areas is confused with the colors adopted for the hands in different conditions. Likewise, the use of dashed and dotted lines is confused in the most important areas of these figures. Why not highlight the first 250 ms on a separate graph?

Finally, the colors adopted by experiment in figure 9 should not be the same colors adopted for each hand in the other figures.

Thank you for these suggestions. I changed the colors in figures and added three new bar charts (Figures 3, 7, and 10) representing grip force averaged by condition in the time windows of interest. As you suggested, I also changed the color coding in Fig. 9 (Fig. 12 in the new version of the manuscript).

R1 – Ok.