

Visuo-tactile interactions are dependent on the predictive value of the visual stimulus



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ABSTRACT

In this study we aimed to explore the predictive link between visual stimuli moving towards the body and the tactile consequences that follow. More specifically, we tested if information derived from an approaching visual stimulus in the region directly surrounding the body (the peripersonal space) could be used to make judgments about the location and time of impending tactile contact. We used moving arm stimuli, displayed on a computer screen, which appeared to travel either towards the face (middle of the left/right cheek) or slightly away from the subject's face. This stimulus was followed by tactile stimulation of the left/right cheek. The time lag between the visual stimulus and tactile stimulation was also manipulated to simulate tactile contact at a time that was either consistent or inconsistent with the speed of the approaching hand. Reaction time information indicated that faster responses were produced when the arm moved towards the hemispace in which the tactile stimulation was delivered and was insensitive to whether the arm was moving towards the cheek or slightly away from the cheek. Furthermore, response times were fastest when the tactile stimulation arrived at the moment that was consistent with the speed of the moving arm. The effects disappeared when the arm appeared to be retracting from the subject's face. These results suggest the existence of a predictive mechanism that exploits the visual information derived from objects moving towards the body for making judgments about the time and location of impending tactile contact.

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1. Introduction

An experience that almost everyone has had is that of being tickled. An aspect common to this experience is the sensation of being tickled even before the other person's hands touch you. This is an illustration of the predictive link between vision and touch. That is, visual information about an approaching stimulus (here the fingers of another person) results in the anticipation of being tickled. This predictive link not only involves the inference of the imminent tactile sensation caused by viewing the causative object, but, also the modulation of the related neural activity in expectation of the tactile consequence, thereby reducing the need for very elaborate processing following the actual event presentation (James, 1890). Indeed, predictive coding allows us to act, and not solely to react once all relevant information has been presented and fully processed, by making predictions about what to expect next while taking into account the current context and previous experiences integrated across different timescales (Bubic et al., 2010).

There have been several reports of how space closely surrounding the body, the *peripersonal space*, is processed differently than other regions. The neural areas representing the (peri-)personal space have been defined in the monkey brain. These studies show that bimodal neurons in premotor and parietal cortex respond to tactile stimuli on the arm or face as well as visual stimuli nearby, but not far away from that body part (Duhamel et al., 1998; Graziano et al., 1997; Rizzolatti et al., 1981). This distinction between the peri- and extra-personal spaces might be useful for filtering information that is likely to be of significance to us.

Firstly, for obvious practical reasons, objects/people in *only* the space closely surrounding us may be interacted with, thereby allowing us to plan approaching movements towards them (Rizzolatti, 1997; Brozzoli et al., 2014). For instance, Farnè and Lâdavas (2000) have behaviourally shown that the use of a tool can dynamically extend the peripersonal space of the hand towards the outward tip of the tool, thereby demonstrating the role of peripersonal space as an interactable space within our surroundings. Furthermore, a study by Brozzoli et al. (2010) showed that when grasping objects, a flash on one side of the target object improved processing of tactile stimuli on the finger that would touch that part of the object at the end of the grasping movement. This effect was particularly clear during execution of the grasping movement.

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These findings suggest a dynamic link between visual information on a nearby object and tactile processing on the approaching hand.

Secondly, objects/people in our close proximity may also pose a threat to us thereby warranting us to initiate defensive movements in response to such perpetrations, such as an object approaching us at high speeds. Detecting this object early would help us either avoid the object, or prepare for contact with it more efficiently. Evidence for such a defensive mechanism can be seen from monkey studies by Cooke and Graziano (Cooke and Graziano, 2004; Graziano and Cooke, 2006) who found that when the regions that respond to looming or nearby objects are artificially stimulated, the animal executes defensive movements like withdrawing or blocking. Similarly, Sambo et al. (2012a,b) have demonstrated that the eye-blink reflex in humans was greater when an external hand was near the subject's face as opposed to when it was further away from the face. Makin et al. (2009) showed that objects that approached a location near the hand (when compared to a location far from the hand) increased cortico-spinal excitability, indicating the preparation of the underlying motor areas of the hand to retract.

Based on these studies, it can be summarised that the space around the body is crucial to monitor in order to protect oneself from an approaching object or to plan movements to interact with a nearby object.

In the context of the *defensive peripersonal space*, we suggest that the mechanism underlying the formation of this defensive zone around our body is visuo-tactile prediction. That is, the time-course and location of an impending tactile stimulus caused by an event/object can be predicted by the visual information conveyed by the same event/object, thereby allowing us to efficiently respond to the object.

The facilitative effects of visual information on detecting tactile stimuli have been demonstrated in behavioural studies investigating the cross-modal allocation of spatial attention (see Driver and Spence, 1998; Macaluso and Maravita, 2010). The main findings of these studies are that when visual attention is directed by a cue to a certain location, the processing of a tactile target at that location is also enhanced. For example, Kennett et al. (2002) showed that judgments about tactile stimuli on the hand were faster when these stimuli had been preceded by a light flash at the same location, and were slower when preceded by a light flash at the opposite hand. Cross-modal allocation of spatial attention, therefore, relies on the physical proximity of the visual cue and the stimulated body-part, by causing visual attention at that location to prioritise the processing of tactile information in the same spatial location.

As physical proximity between the visual cue and the site of tactile target delivery was common to these studies, it is difficult to determine if similar behavioural visuo-tactile interactions can be found when visual information predicts a tactile stimulus, but when the two are not near each other. If visuo-tactile interactions can underlie a defensive strategy, it should also be possible to extract information about the impending location and time of contact with an approaching object, before the object reaches the space near the observer. That is, if a true predictive link is to be established between vision and touch, one has to be able to demonstrate that the information derived from viewing a visual cue at a certain location, can cause the allocation of tactile attention at the implied location of contact, (which may be at a distance from the displayed visual information) and at the implied time of contact. It is also crucial to ascertain that such a spatial shift in attention is caused solely by the *expectation* of a tactile event at that location.

The aim of the current study is to test if such a predictive link between vision and touch can be found. That is, will the information obtained by viewing an approaching object enhance

tactile processing at the impending time and location of contact with the object, without having to visually follow the trajectory of the object's motion towards the stimulated site?

In our first experiment, we used videos of a moving human arm approaching the subject's face or moving slightly away from it. These were displayed on a computer monitor placed parallel to the subject. Following this, a tactile target was delivered on subject's face either at a location concurrent to the trajectory of the moving arm, or at a non-concurrent location. The subject was asked to provide a speeded response as soon as the tactile target was detected. The time lag between the visual cue and the tactile target was also manipulated. With this setup, we tested if:

1. The coincidence of the implied *location* of contact with the arm and the *site* of tactile target delivery will cause the tactile target to be detected faster (property 1).
2. The coincidence of the implied *time* to contact with the arm and the *time* of the tactile target delivery will cause the tactile target to be detected faster (property 2).

We also conducted a second experiment in order to verify that any effects found in the first experiment were indeed caused by the arm moving *towards* the subject. In the second experiment, we displayed videos of a human arm retracting from the subject's face. This was followed by a tactile target on one of the subject's cheeks. The subject again was asked to respond as soon as the tactile target was detected. Since the arm was retracting from the subject, we expected that neither the trajectory nor the speed of the arm movement would have an impact on where and when the subject expected the tactile target.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Sixteen subjects (3 males, and 3 left-handers) from Utrecht University between the ages of 18–30 ($M=22.3$, $SD=2.68$) were recruited. All subjects were naïve to the purpose of the study and received either study credit or money as compensation. All subjects gave informed consent and were aware that their information would be kept confidential and that they were free to leave the experiment at any time. The experiment was conducted in agreement with the local ethics and safety guidelines, which are based on the Declaration of Helsinki.

2.1.2. Visual stimulus preparation

The stimuli were a set of images that depicted a moving hand that approached the subject from a distance of 60 cm. They were created in our lab for use in the study.

2.1.2.1. Procedure for capturing images. The images of the hand were created in the lab by photographing a Caucasian male volunteer who was 28 years old. The volunteer was asked to dress in a black full-sleeved shirt. The volunteer sat in a chair in front of a camera. A table was placed in between the camera and the volunteer such that the edge of the table closest to the volunteer was touching his chest and his legs were completely under the table. The camera was placed directly opposite the volunteer, facing him, and this position was fixed for the entire photo-session. The camera lens was level with the shoulder of the volunteer. The volunteer was asked to sit with his hands folded into fists and placed in front of him on the table, with the table still touching his chest. The left and right fists were placed right next to each other and the front of the fist was facing the camera and was at a

distance of 60 cm from the camera. This position was called the 'rest condition' and was represented by the name *frame 1* in the image set. After this, the volunteer was asked to point with his right hand to one of the predetermined destinations (explained in the next section) in front of him, without displacing his hand (*Frame 2*). From this point on, with his finger (index finger of the right arm, hereby referred to as *finger*) still pointing towards the destination, he was asked to move his right hand in steps of 3.4 cm towards the destination (*Frames 3–10*). This was repeated 8 times, so that the hand moved a total of 30 cm ($9 \times 3.4 = 30.6$ cm, to be precise) towards the destination and hence was also 30 cm closer to the camera. The left arm remained in the rest position throughout the entire session. An image of the hand with the volunteer was taken at the rest position and at every consequent position of the movement (i.e., at the 10 equidistant subsequent positions of the hand), thereby yielding a series of 10 frames for an arm moving from rest towards a preset destination in front of it.

This procedure was repeated 4 times and yielded 4 sets of 10 images for 4 different locations/trajectories of motion. The first image of every set (*Frame 1*) always represented the rest position. The destinations were created to represent the hand pointing in the general direction of an imaginary subject seated facing the volunteer, and 60 cm away from him. More specifically, the right arm of the volunteer was moving and pointing towards the right cheek of the imaginary subject, or slightly away from the right cheek of the imaginary subject (therefore moving away from his face), or towards the left cheek of the imaginary subject, or slightly away from the left cheek of the imaginary subject (therefore moving away from his face) (Fig. 1a–e).

All images were 30 cm high and 54 cm wide. In the rest image, the arms took up 17.5 cm vertically (vertical distance between the shoulder and the table), and 18.9 cm horizontally distance between the 2 elbows. Most importantly, the images were captured such that the arm looked comparable in size to a real arm placed at that particular distance from the subject. Fig. 1a depicts the size of the image and its constituents. As the arm started moving closer to the subject, the amount of space it occupied on the image, also increased proportionally.

In order to guide the movement of the hand, a grid (80×60 cm²) was placed on the table with the four trajectories of the motion and the intermediate positions marked clearly on it.

2.1.2.2. Image processing. Adobe Photoshop CS5 software was used to isolate the left and right arm and hand, after which a grey background was added.

The images were flipped with respect to the vertical plane to create the motion of the volunteer's left arm with the right arm being held at rest, resulting in a total of 8 sets of 10 images with *frame 1* representing the same rest position for all the sets.

2.1.3. Apparatus and stimuli

The actual experiment was conducted in an experiment room in the Utrecht University premises. The room was darkened throughout the duration of the experiment.

2.1.3.1. Visual stimuli. As described above, there were 8 sets of stimuli used in the experiment based on the trajectory/destination of the arm movement and the laterality of the moving arm (left or

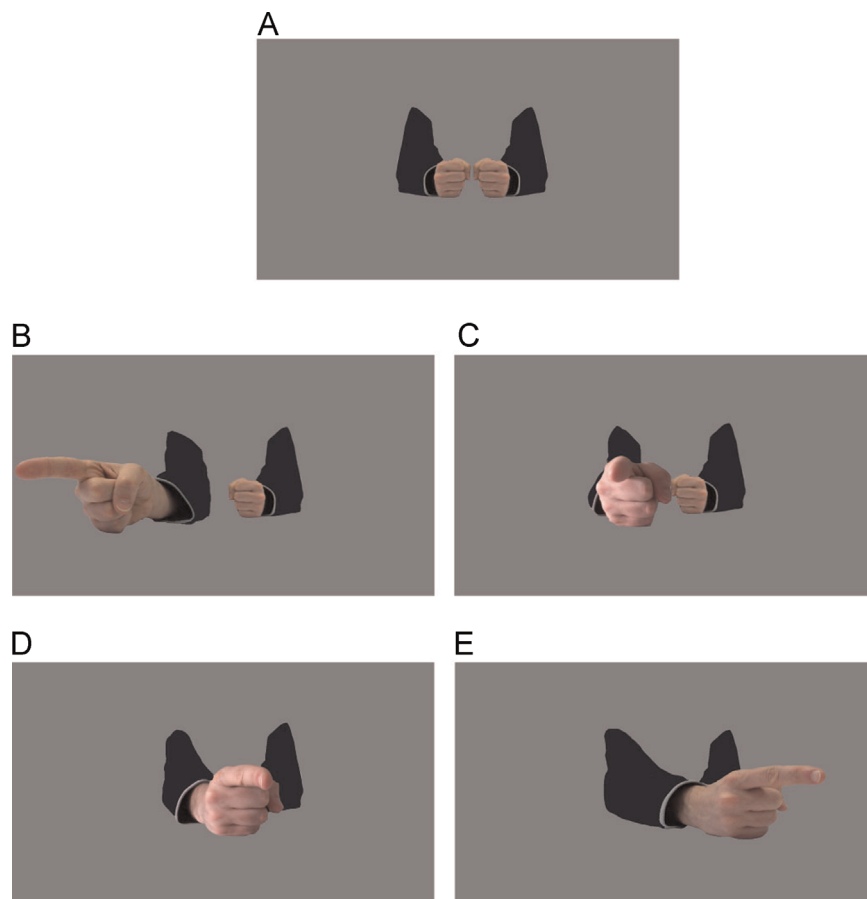


Fig. 1. Right arm destinations as seen by the subject. 1a. The arm is at rest position (*Frame 1*, common to all image sets). 1b. The arm has moved away from the ipsi-hemisphere cheek of the subject (*destination 1, Frame 10*). 1c. The arm has moved towards the ipsi-hemisphere cheek of the subject (*destination 2, Frame 10*). 1d. The arm has moved towards the contra-hemisphere cheek of the subject (*destination 3, Frame 10*). 1e. The arm has moved away from the contra-hemisphere cheek of the subject (*destination 4, Frame 10*).

right arm). Based on the laterality of the moving arm, the finger could point to one of the four destinations. This definition of hand destination will be used throughout the rest of the paper.

Destination 1: Pointing slightly away from the ipsi-hemisphere cheek (Fig. 1b). That is, if the right arm was moving, it pointed away from the left cheek of the subject (who was facing the arm). If the left arm was moving, it pointed away from the right cheek of the subject.

Destination 2: Pointing towards the ipsi-hemisphere cheek (Fig. 1c).

If the right arm was moving, it pointed towards the left cheek of the subject. If the left arm was moving, it pointed to the right cheek of the subject.

Destination 3: Pointing towards the contra-hemisphere cheek (Fig. 1d).

If the right arm was moving, it pointed towards the right cheek of the subject. If the left arm was moving, it pointed to the left cheek of the subject.

Destination 4: Pointing slightly away from the contra-hemisphere cheek (Fig. 1e). If the right arm was moving, it pointed away from the right cheek of the subject. If the left arm was moving, it pointed away from the left cheek of the subject.

By using four destinations, we wanted to test if response times are facilitated only if the finger pointed at the exact location of the tactile stimulus (Destination 1 vs. Destination 2, and Destination 3 vs. Destination 4). Also, we wanted to test if response times affected if the finger pointed at the opposite hemisphere from its origin (Destination 2 vs. Destination 3).

One of the 8 sets of images was selected randomly on every trial, and each image in the selected set was displayed on the screen in rapid succession to create the illusion of motion of the hand towards one of the four aforementioned destinations on the subject's face.

The visual stimuli were displayed on a computer monitor (Iiyama 22 in. LCD monitor) with a frame-rate of 60 Hz. Matlab (R2008a) software on a Windows platform was used to run the experiment.

2.1.3.2. Tactile stimuli. The tactile targets were 180 Hz vibrations that were delivered to one of the subject's cheeks every trial, for a period of 100 ms by way of 2 vibro-tactile motors attached to the subject's face. The left and right vibro-tactile motors were attached at the junction of the horizontal and vertical midpoints of the respective cheeks.

2.1.3.3. Stimulus onset asynchronies. One goal of this study was to test the temporal predictive quality of an approaching visual cue. Therefore, the time differences between the onset of the arm's motion stimuli and the delivery of the tactile target were manipulated by using the time to contact of the arm with the subject's face, as a reference. The arm appeared to start 60 cm from the subject and stopped moving at 30 cm in front of the subject, thereby requiring moving an additional 30 cm to reach the subject. If the arm travels the first 30 cm at constant speed in x ms, it must also travel the last (un-depicted) 30 cm, thereby reaching the subject's face in x ms. Therefore, from the onset of the movement, the subject should expect a touch in $2x$ ms. This contingency was manipulated such that it was equiprobable to receive a tactile stimulus in $1.5x$, $2x$, or $2.5x$ ms following the onset of the motion (or $0.5x$, x , or $1.5x$, after the cessation of motion) in every trial.

2.1.3.4. Responses. The subject was asked to respond to the tactile-stimulus by pressing a single button on the response box. The subjects were asked to respond using the same pre-set button

throughout the entire experiment, irrespective of the destination of the visual cue or the laterality of the tactile targets. The subject responded with his dominant hand.

2.1.3.5. Motor noise masking. The noise of the motors was masked by playing white noise over a pair of headphones (Sennheiser HD 202) throughout the experiment. This was done to ensure that the subject responded only to the feel of the vibration and not to its sound.

2.1.4. Procedure

The subject was seated in front of the computer screen. His head was fixated at a distance of 30 cm from the screen using a chin rest. The height of the chin rest and the screen were adjusted to suit the height of the subject. Most importantly, the screen was adjusted to ensure that the moving hand stimuli pointed at the right locations on the subject's face, and this was accomplished by setting the height of the screen such that, the outstretched arm image was at the same vertical level as the attached vibrotactile motors. This was done by visual inspection. During this process, by looking at the last static image in each of the four image-sets (4 destinations, either depicting the motion left, or right arm), the subjects were asked to identify the location that they felt the arm was pointing at. All the subjects were able to correctly identify whether the arm was pointing at their cheek or away from their face. The response box was placed centrally in front of the subject. Headphones were placed on the subject to deliver the masking white-noise.

The experiment consisted of 4 blocks of 270 trials each. Each of the 24 conditions occurred 36 times. The remaining 216 trials (54 per block) were catch trials to discourage subjects from responding before the tactile target occurs.

Every trial began with the presentation of a black fixation cross on a grey background. This lasted for 800–1000 ms in every trial. Subjects were told keep their eyes fixated at the location the fixation cross was initially displayed throughout the trial. Following the display of the fixation cross, the *Frame 1* (rest position) image was displayed for 166.7 ms (10 screen ticks). This was followed by 9 images from one of the 8 sets (moving to one of the four destinations). Each image was displayed for 33.34 ms (2 screen ticks). Therefore, the moving arm images (*frames 2–9*) took

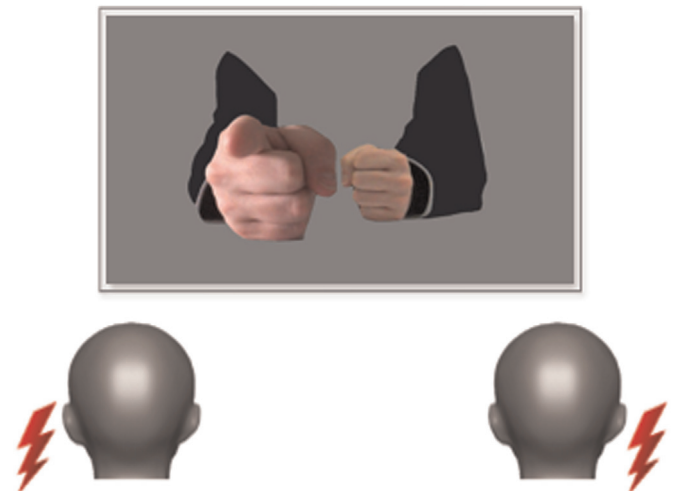


Fig. 2. The Congruency conditions. The subject is sitting facing the computer screen where the images of the moving arms are displayed. If the tactile target is delivered to the subject in the same hemisphere as the arm's pointing location (depicted on the bottom left), then the trial is a congruent trial. If the tactile target is delivered to the subject in the opposite hemisphere as the arm's pointing location (depicted on the bottom right), then the trial is an incongruent trial.

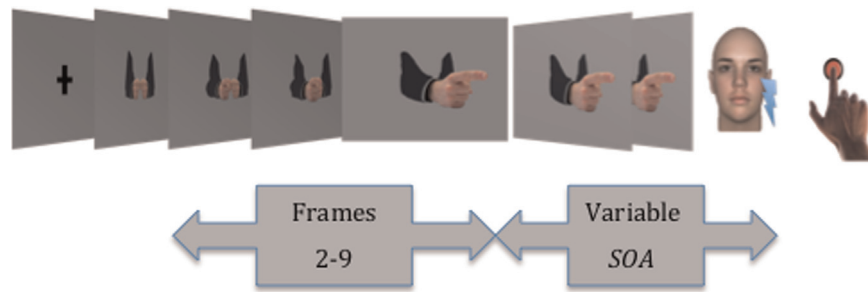


Fig. 3. The experimental set up. Each trial starts with a fixation cross, followed by the presentation of the arms-at-rest stimulus. The arm then starts moving towards one of the four destinations. The arm eventually stops moving, and after the SOA (early, on-time, late) duration has passed, a tactile target is delivered on either the left or right cheek of the subject. The subject then responds to the tactile stimulation by pressing a button.

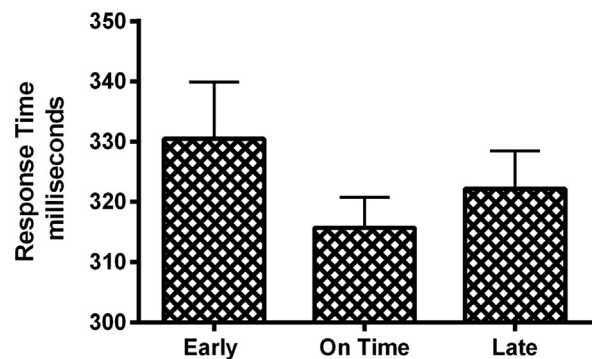
266.72 ms ($2 \times 8 \times 16.67$) to complete their motion. The last frame (frame 10) was displayed following frame 9, and lasted until the end of the trial (always 1100 ms following the onset of frame 10). The tactile stimulus was delivered 133 ms (Early SOA), 266 ms (OnTime SOA), or 400 ms (Late SOA) following the onset of frame 10. In the case of a catch trial, no tactile stimulus was delivered in this 1100 ms duration and the subject was instructed not to respond in this case.

The tactile stimulus was delivered on one of the two cheeks of the subject and the subjects were asked to respond to it as quickly as possible. If the tactile target was delivered in the same hemisphere that the finger was pointing towards, then that was called a *congruent* trial. If the tactile target was delivered in the opposite hemisphere that the finger was pointing towards, then that was called an *incongruent* trial. Fig. 2 illustrates the congruency conditions. Subjects were instructed that the moving arm stimuli contained no information about when and where the tactile target occurred. Therefore, there were 4 variable conditions for every trial: the laterality of the moving arm (left or right arm), the destination of the moving arm (4 Destinations), the congruency of the tactile target with respect to the finger's pointing location (2 Congruencies), and the time of delivery of the tactile target (3 SOAs). Fig. 3 depicts a schematic presentation of an experimental trial. One point to note in this study is that, although we used moving hand stimuli as approaching objects, the constant speed of the hand images keeps it from simulating real biological hand motion. Real moving hands attempting reach movements demonstrate a bell shaped speed pattern when moving along a straight path (Abend et al., 1982).

2.2. Results

The response times were calculated from the onset of the 100 ms tactile stimulus. Median response times were calculated per condition for each individual, and a mean for the different conditions was calculated for the whole group. One subject was removed from the analysis, as his response times were greater than 2 standard deviations of the group mean ($M=343.16$, $SD=83.083$). False alarms were analysed and one subject was removed due to excessive error rates in the catch trials ($> 25\%$). The false alarms for other subjects were very rare ($M=2.2\%$, $SD=2.3\%$). The remaining response times (14 subjects) were analysed using a $3 \times 4 \times 2$ repeated measures ANOVA. The arm-laterality (left/right) conditions were collapsed and therefore not analysed separately. The within subject factors were SOA (early, on-time, and late), destination (away ipsi-hemisphere cheek, towards ipsi-hemisphere cheek, towards contra-hemisphere cheek, away contra-hemisphere cheek), and congruency (congruent vs. incongruent). The average response times for the different SOAs and congruencies can be seen in Fig. 4. The response times plotted per SOA and congruency can be seen in Fig. 5. The error bars for each condition were created by calculating the confidence intervals

Experiment 1: Response times per SOA



Experiment 1: Response times per Congruency

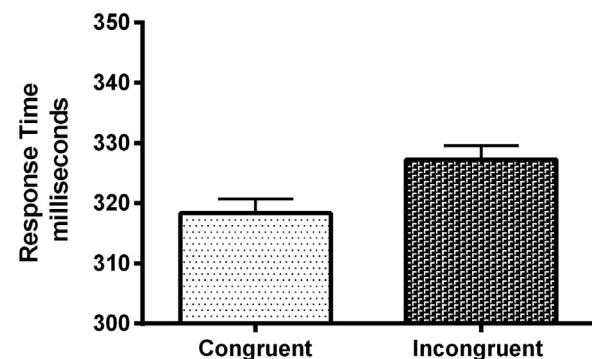


Fig. 4. Response times in Experiment 1. The top graph shows the mean response times plotted per SOA. The response times for On Time SOA are shorter than for the Early and Late SOAs. The bottom graph shows the response times plotted per Congruency. Response times in the Congruent condition are shorter than the response times in the Incongruent condition. The error bars for each condition were created by calculating the confidence intervals ($\alpha=0.05$) after correcting for between subject differences in the scores.

($\alpha=0.05$) after correcting for between subject differences in the scores (Field, 2000).

The ANOVA revealed significant effects of SOA ($F(1.28, 16.63)=9.91$, $p=0.004$).¹ Pairwise comparisons with Bonferroni corrections between the SOA Early vs. On-time revealed that the response times for the On-time condition were significantly faster ($p=0.004$). Similarly, comparison between the SOA Late vs. On-Time revealed that the response times for the On-time condition were significantly faster ($p=0.007$). The Early and Late SOAs did not differ from one another ($p=0.188$).

¹ Corrected for sphericity using the Greenhouse–Geisser procedure.

Experiment 1: Response Times Per SOA and Congruency

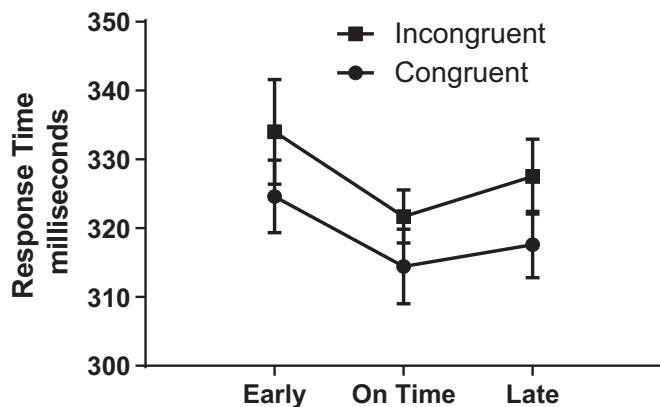


Fig. 5. Response times in Experiment 1 plotted per SOA and congruency. Response times in the Congruent On-time SOA condition are shorter than all the other conditions. The error bars for each condition were created by calculating the confidence intervals ($\alpha=0.05$) after correcting for between subject differences in the scores.

The *Congruency* factor revealed a significant main effect ($F(1,13)=16.65$, $p<0.001$), with response times for the congruent condition being faster than the incongruent condition. The results of the ANOVA revealed that the *Destination* factor did not show a significant main effect ($p=0.432$). None of the factors interacted significantly.

2.3. Discussion

The results of this experiment showed that response times in the *on-time* SOA condition were significantly faster than the *early* and *late* SOA conditions. The *early* and *late* SOA conditions did not differ significantly from one another.

Subjects also responded faster when the tactile target was delivered in the same hemispace as that the finger was pointing towards. However, there were no differences between the exact locations that the finger was pointing at. The significant effect of *congruency* (tactile target being delivered in the same or opposite hemispace that the finger was pointing towards) provides support to our hypothesis that the responses are facilitated when the tactile target is delivered at a location that is predicted by the trajectory of the moving hand. That is, even though exact location of pointing within a hemispace did not seem to facilitate responses (whether the finger pointed exactly towards or slightly away from the stimulated location), responses were facilitated when the finger pointed towards the same hemispace as the tactile-target delivery (Destinations 1 and 2 did not differ from one another and Destinations 3 and 4 did not differ from one another). Also, it did not matter if the finger pointed in the same hemispace as it originated from (laterality) or crossed its hemispace of origin and pointed towards the opposite hemispace (destinations 1 and 2 did not differ from destinations 3 and 4). In summary, as long as the finger pointed towards the same hemispace in which the tactile target was delivered, response times were faster in all the SOA conditions.

No factors interacted significantly. An interesting implication of the lack of interaction between *congruency* and *SOA* is that the effects of temporal and spatial prediction of the impending tactile target act independently of one another. Fig. 5 shows the plot of the response times per SOA and congruency. The size of the congruency effects ($RT_{\text{Incongruent}} - RT_{\text{Congruent}}$) was similar for the

different SOA conditions. However, the response time for the *congruent on-time* SOA condition was the shortest, indicating that subjects responded fastest when the tactile target was delivered in the expected hemispace and at the expected time-to contact.

Overall, these results suggest the presence of a visuo-tactile predictive mechanism, which takes into account the speed of the moving arm when predicting *when* the tactile target will occur, and the general direction of the pointing finger when predicting *where* the tactile target will occur.

In order to verify that the faster responses found in the on-time condition were indeed caused by the information caused by the arm moving *towards* the subject, a follow-up experiment was conducted with the same images, but where the arms retracted from the subject.

3. Experiment 2

3.1. Methods

In *Experiment 2*, the frames were presented in a reverse order to give an impression that the arm was retracting from the subject.

3.1.1. Participants

Fifteen subjects (6 males, and 1 left-hander) were recruited. All subjects were naïve to the purpose of the study. All subjects were between 18–30 years of age (Mean=24.85, SD=2.31). They received either study credit or money as compensation. The experiment was conducted in agreement with the local ethics and safety guidelines, which are in accordance with the Declaration of Helsinki.

3.1.2. Procedure

The procedure resembled that of experiment 1, with the exceptions that:

1. The frames were presented in the reverse order, i.e., from *frame 10* to *frame 1*.
2. Only the *destination 1* image set was used. We decided to use only one arm *destination* as we found no differences in responses based on the destination of the moving arm in the previous experiment.

3.2. Results

The response times were calculated from the onset of the 100 ms tactile stimulus. The response times for a subject per condition were calculated by taking the median of the scores in the condition. Group mean scores were calculated by taking a mean of the individual subject scores per condition. False alarms in catch trials were rare ($M=2.0\%$, $SD=4.1\%$). One subject was removed from the analysis, as his response times deviated more than two standard deviations from the group mean ($M=329.86$, $SD=120.59$). The remaining 14 participants' response times were analysed using a 3×2 repeated measures ANOVA. The arm-laterality (left/right moving arm) conditions were collapsed and therefore not analysed separately. The within-subject factors were *SOA* (early, on-time, and late) and *congruency* (congruent vs. incongruent) and the dependent variable was the response time. There was no main effect of *SOA* ($p=0.436$). *Congruency* was also not significant ($p=0.146$) and there were no interaction effects. The average response times per SOA and Congruency can be seen in Fig. 6. The error bars for each condition were created by calculating after correcting for between subject differences in the individual scores (Field, 2000).

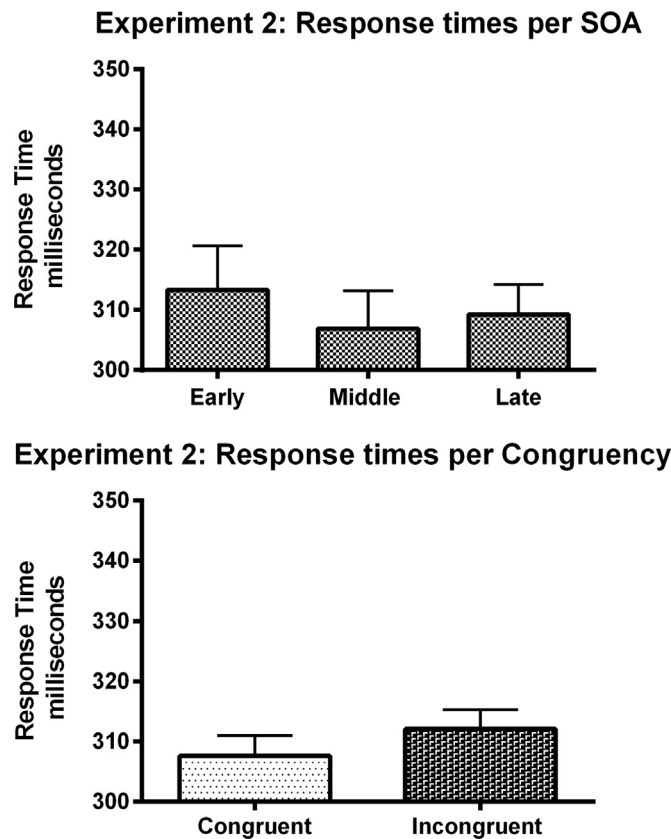


Fig. 6. Response times in experiment 2: The top graph shows the response times plotted per SOA. The response times do not differ per SOA condition. All the SOAs are numerically the same as in Experiment 1. The “On-Time” SOA condition from Experiment 1 has been renamed as the “Middle” SOA in this graph. The bottom graph shows the response times plotted per Congruency. The response times do not differ per congruency condition. The error bars for each condition were created by calculating the confidence intervals ($\alpha=0.05$) after correcting for between subject differences in the scores.

3.3. Discussion

The results of *Experiment 2* seem to yield strength to the main hypothesis that the response times will be faster when the tactile target is delivered at the expected time and location, *only* when physical contact with the hand is anticipated. When an object retracts from the observer and reaches a neutral rest-position, there is no expectation created towards the time or location of the impending target. Taken together, *Experiment 2* shows that movement towards the observer is necessary for a visuo-tactile prediction to be generated.

4. General discussion

The present study aimed at investigating whether temporal and spatial information contained in a stimulus approaching an observer can be used by the visuo-tactile system to predict the location and the time of contact with the object. In *Experiment 1*, we tested this hypothesis by presenting images of a moving arm approaching the subject, or moving slightly away from the subject, at a constant speed, and by varying the time and location at which the subject received a tactile stimulus. The results showed that subjects responded faster when the tactile target was delivered at the time that the arm would touch them. Also, when spatial separations between the expected contact location and the stimulated location were large, i.e., when the implied location and stimulated location were in opposite hemispaces, there were

significant differences in response times. This was evidenced by responses in *congruent* condition being significantly shorter than in the *incongruent* condition.

Interestingly, the response times to the tactile targets, when the finger pointed directly towards the stimulation site, or slightly away from it, did not prove to be significantly different from each other. This might fit the notion that the visual receptive fields of bimodal neurons in monkeys extend a few centimeters outwards from the tactile receptive fields in a manner that circumscribed the tactile area (Rizzolatti, 1997). If bimodal neurons in the human brain can be assumed to function similarly, then in the *away* conditions (destinations 1 and 4) in our experiment, when moving arm was slightly away from the cheek, it might still have been close enough to the cheek to be included in the visual receptive field of the actual region of tactile stimulation.

The neural mechanism underlying the pattern of reaction times found in the present study may be similar to that described in an earlier study by Carlsson et al. (2000). The authors found, for both *anticipated* and real tickling experiences, that the contralateral somatosensory (SS) areas showed increased activation while the SS areas located outside the area representing the target stimulus decreased their activity. Therefore, an increase in activation at the SS site of the expected tactile contact, along with a decrease in activation in the non-corresponding SS areas are a plausible cause for the respective reduction and increase of response times found when spatial expectations were manipulated.

The mechanism underlying the temporal facilitation effect found in this study has been shown also in other studies conducted in the visual domain. For example, recently Seibold and Rolke (2014) examined if temporal expectation about an impending target (which may be presented in a random spatial location) reduces the distracting effects of the sudden onset of a task irrelevant item. The authors found that this was not the case and concluded the temporal expectation influences overall early visual processing independent of spatial location. Similarly in the present study the response times in the *incongruent on-time* condition were lower than the other *incongruent* conditions (*Early* and *Late*) demonstrating that the temporal facilitation benefitted subjects in this condition, even when the tactile target was delivered at an unexpected location. The lack of interaction effects found in this study when both spatial and temporal expectations were met, seems to suggest that the two factors act independently of one another. This pattern of the independence of the spatial and temporal facilitation effects found in the present study can be further extrapolated from a previous study by Doherty et al. (2005). The authors investigated the interplay between temporal and spatial expectations on attention in a visual task. Firstly at the behavioural level, they found that both temporal and spatial expectations enhanced response times comparably, but the response times were fastest when both the expectations were met, and slowest when no expectation was met.

Furthermore, when studying the underlying ERP components of these effects, Doherty et al. (2005), found that when only the temporal expectation was met, response-specific components were enhanced. When only the spatial expectation was met, early perceptual components were enhanced. When temporal and spatial expectations were both met, the early perceptual components were further enhanced along with the response-specific components, thereby indicating that temporal and spatial expectations effect stimulus processing at different stages, independently and additively.

Experiment 2 was identical to *Experiment 1*, except the direction of travel of the hands was reversed. This manipulation, however, resulted in the disappearance of the temporal and spatial facilitation effects. This indicates that the expectation of a tactile stimulus created by a visually approaching target is the crucial factor

in the observed pattern of response times found in *Experiment 1*. It is interesting to note that the lack of a spatial cross-modal congruency effect in *Experiment 2*. This may be due to the fact that the hands travel back and settle in the neutral position a minimum of 133 ms before the tactile stimulus is delivered, thereby not cueing a hemispace in the period before the tactile stimulation. In contrast, in some simple visuo-tactile cueing paradigms, when a target was delivered at a location that was previously cued even around 300 ms ago, reaction times were found to be facilitated (Driver and Spence, 1998). When compared to these tasks, one would expect to see a cueing effect for at least the early SOA condition. The absence of the effect might indicate that people indeed were sensitive to the direction of the hands travel (retracting), thereby expecting no tactile stimulation at all.

Our study demonstrates that the information obtained by viewing an approaching object, would enhance tactile processing at the impending time and location of contact with the object, without having to visually follow the trajectory of the object's motion towards the stimulated site. As the illusion of the arm's motion towards the subject was created using changing pictorial information, the subjects' gaze could not follow the implied trajectory of the moving arm towards their face. Furthermore, the visual information was always displayed at the same location in depth (on a computer monitor).

A study by Grey and Tan (2002) similarly investigated the predictive links between vision and touch. They also found that, subjects responded faster to the subsequent tactile target if the target was delivered at the time and location at which the object would touch the hand. However, due to the construction of their study, it is not possible to rule out that subjects moved their gaze along the trajectory of the moving object, towards the location of the impending tactile stimulus. Therefore, their results can also be explained as being caused by overt visual attention being directed to the stimulation site, just prior to the stimulation, thereby enhancing tactile processing at that time and location. That is, it cannot be said with certainty that the mere expectation of the tactile target was the cause for the enhancement of tactile processing at the future site of stimulation. In our study it was impossible to follow the implied trajectory of the moving arm, therefore, our results indicate that subjects were indeed able to use spatial and temporal information implied by the visual cue to enhance tactile processing of the target. The pattern of the results seem to suggest that people use both temporal and spatial information in creating an expectation about the time and location of tactile contact.

Evidence from previous studies suggests that people are capable of extracting the projected point of impact of an object approaching the face. Neppi-Mòdona et al. (2004) found that people were quite good at predicting the impact location on their face of an approaching stimulus, even when they had to imagine the latter half of the object's movement trajectory towards their face, with their eyes closed. Duhamel et al. (1998) demonstrated the existence of neurons in the ventral intraparietal sulcus of the monkey brain that provided bimodal responses to visual stimuli whose projected impact point (based on the stimulus's movement trajectory) was spatially congruent with the location of the tactile stimulation. This type of mechanism may also subserve the prediction of an impending tactile stimulus based on visual input as observed in the current study. A study that shows evidence for such a predictive nature of visuo-tactile interactions was conducted by Beauchamp et al. (2010). In particular, they assessed the effects of the reliability of visual and tactile information given to subjects and used fMRI to determine the underlying neural network. They demonstrated a weighting mechanism that takes into account the relative reliability of the stimuli in both modalities (i.e., clarity of the visual information and the clarity of the felt touch) in

determining whether or not a touch has occurred. Their results indicated that subjects reported an undelivered touch (indicating inaccurate subject responses) when clear visual information corresponding a touch was presented. Moreover, they showed that connectivity between somatosensory areas and the intraparietal sulcus (IPS) was increased when somatosensory information was more reliable and the connectivity between visual areas and IPS was enhanced when visual information was more reliable. Furthermore, Pasalar et al. (2010) demonstrated that the posterior parietal cortex is crucially involved in such visuotactile interactions.

The results in the present study lead to the possibility that the mechanism underlying visuo-tactile prediction is a cross-modal attentional shift towards the location of the impending tactile contact. That is, while viewing an object approaching your face, your attention is shifted to the location of the face, which the object will eventually touch. Therefore, there is a shift in attention from one location to another (from the location of the approaching object towards the location on your face), and there is a shift in modality (viewing an approaching object causes tactile attention to be enhanced). Previous paradigms used in investigating visuo-tactile attentional shifts have relied on the physical proximity between the visual cue and tactile target. However, their dependence on this proximity might be due to the nature of visual cues, (usually light flashes and arrows) which do not contain inherent information about event that is to follow. That is, viewing a light flash does not imply a touch on the body, whereas viewing an object approaching one's body does imply a touch on the body. Hence, a flash of light can draw attention towards a body-part only if the two are close together. Also, these attentional effects are short-lived, typically lasting only for around 300 ms (see Driver and Spence, 1998; Macaluso and Maravita, 2010).

Nevertheless, these cross-modal shifts in spatial attention might still be viewed as the most basic illustration of the formation of a defensive zone around the body. That is, the sudden onset of a light flash may indicate that an unknown event of significance might follow it, thereby causing the person to monitor that region for a short while. However, when the visual cue is infused with more specific information about the event that is to follow, the allocation of attention can then be specific to the location and moment of the following event. In conclusion, our results suggest that, by viewing an object approaching the body, we are able to extract implicit information about the time and location of a future tactile stimulus. By doing so, we are better at executing an appropriate response to the event. Visuo-tactile prediction may hence be viewed as the mechanism underlying the formation of the defensive zone around the body, the *peripersonal space*.

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References

- Abend, W., Bizzi, E., Morasso, P., 1982. Human arm trajectory formation. *Brain* 105, 331–348.
- Beauchamp, M.S., Pasalar, S., Ro, T., 2010. Neural substrates of reliability-weighted visual-tactile multisensory integration. *Front. Syst. Neurosci.* 4 (25), 1783–1790.
- Brozzoli, C., Cardinali, L., Pavani, F., Farnè, A., 2010. Action-specific remapping of peripersonal space. *Neuropsychologia* 48 (3), 796–802.
- Brozzoli, C., Ehrsson, H.H., Farnè, A., 2014. Multisensory representation of the space near the hand: from perception to action and interindividual interactions. *Neurosci.* 20 (2), 122–135.
- Bubic, A., von Cramon, D.Y., Schubotz, R.I., 2010. Prediction, cognition and the brain. *Front. Hum. Neurosci.* 4 (25).

- Carlsson, K., Petrovic, P., Skare, S., Petersson, K.M., Ingvar, M., 2000. Tickling expectations: neural processing in anticipation of a sensory stimulus. *J. Cognit. Neurosci.* 12 (4), 691–703.
- Cooke, D.F., Graziano, M.S.A., 2004. Sensorimotor integration in the precentral gyrus: polysensory neurons and defensive movements. *J. Neurophysiol.* 91 (4), 1648–1660.
- Doherty, J.R., Rao, A., Mesulam, M.M., Nobre, A.C., 2005. Synergistic effect of combined temporal and spatial expectations on visual attention. *J. Neurosci.: Off. J. Soc. Neurosci.* 25 (36), 8259–8266.
- Driver, J., Spence, C., 1998. Cross-modal links in spatial attention. *Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci.* 353 (1373), 1319–1331.
- Duhamel, J.R., Colby, C.L., Goldberg, M.E., 1998. Ventral intraparietal area of the macaque: congruent visual and somatic response properties. *J. Neurophysiol.* 79 (1), 126–136.
- Farnè, A., Làdavas, E., 2000. Dynamic size-change of hand peripersonal space following tool use. *Neuroreport* 11 (8), 1645–1649.
- Field, Andy, 2000. *Discovering Statistics Using SPSS for Windows: Advanced Techniques for Beginners*. Sage Publications, Inc, Thousand Oaks, CA, USA, (ISBN:0761957553).
- Gray, R., Tan, H.Z., 2002. Dynamic and predictive links between touch and vision. *Exp. Brain Res. Exp. Hirnforsch. Exp. Céréb.* 145 (1), 50–55.
- Graziano, M., Cooke, D., 2006. Parieto-frontal interactions, personal space, and defensive behavior. *Neuropsychologia* 44 (6), 845–859.
- Graziano, M.S., Hu, X.T., Gross, C.G., 1997. Visuospatial properties of ventral premotor cortex. *J. Neurophysiol.* 77 (5), 2268–2292.
- James, William, 1890. *The Principles of Psychology*. H. Holt Publications, New York (ISBN 0-674-70625-0).
- Kennett, S., Spence, C., Driver, J., 2002. Visuo-tactile links in covert exogenous spatial attention remap across changes in unseen hand posture. *Percept. Psychophys.* 64 (7), 1083–1094.
- Macaluso, E., Maravita, A., 2010. The representation of space near the body through touch and vision. *Neuropsychologia* 48 (3), 782–795.
- Makin, T.R., Holmes, N.P., Brozzoli, C., Rossetti, Y., Farnè, A., 2009. Coding of visual space during motor preparation: approaching objects rapidly modulate corticospinal excitability in hand-centered coordinates. *J. Neurosci.: Off. J. Soc. Neurosci.* 29 (38), 11841–11851.
- Neppi-Mòdona, M., Auclair, D., Sirigu, A., Duhamel, J., 2004. Spatial coding of the predicted impact location of a looming object. *Curr. Biol.* 14, 1174–1180.
- Pasalar, S., Ro, T., Beauchamp, M.S., 2010. TMS of posterior parietal cortex disrupts visual tactile multisensory integration. *Eur. J. Neurosci.* 31, 1783–1790.
- Rizzolatti, G., 1997. The space around us. *Science* 277 (5323), 190–191.
- Rizzolatti, G., Scandolara, C., Matelli, M., Gentilucci, M., 1981. Afferent properties of periaruate neurons in macaque monkeys. II. Visual responses. *Behav. Brain Res.* 2 (2), 147–163.
- Sambo, C.F., Forster, B., Williams, S.C., Iannetti, G.D., 2012a. To blink or not to blink: fine cognitive tuning of the defensive peripersonal space. *J. Neurosci.: Off. J. Soc. Neurosci.* 32 (37), 12921–12927.
- Sambo, C.F., Liang, M., Cruccu, G., Iannetti, G.D., 2012b. Defensive peripersonal space: the blink reflex evoked by hand stimulation is increased when the hand is near the face. *J. Neurophysiol.* 107 (3), 880–889.
- Seibold, V.C., Rolke, B., 2014. Does temporal preparation speed up visual processing? Evidence from the N2pc. *Psychophysiology* 51 (6), 529–538.