Extrinsic Tau-Coupling and the Regulation of Interceptive Reaching Under Varying Task Constraints

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Abstract

We investigated a general theory accounting for the guidance of ongoing movements in an interceptive reaching task. The aim was to assess the premise of tau-coupling that the coupling constant k, the ratio of taus (τs) of motion gaps between hand and object, reflects the kinematics of the on-going movement. The spatial and temporal constraints of the interceptive action were manipulated in three task conditions. While the time dependent counterpart of k, K(t) exhibited task effects, k itself could not distinguish between task manipulations. K(t) showed large variability during the initial acceleration phase, small variability during the rest of the movement, and task dependent changes during the final deceleration phase of interception. The findings highlight the importance of clarifying what constitutes as τ-coupling.

Keywords: Motion and sensory gaps, tau-coupling, kinematics, hand transport, Kappa

Extrinsic tau-coupling and the regulation of interceptive reaching under varying task constraints

Lee (1998) presented a general theory accounting for the guidance of goal directed movements across a range of different modalities. With this *general tau theory* Lee described a mathematical model in which tau (τ), a variable that directly specifies time-to-contact information, could be used to regulate the kinematics of ongoing movements. Two different types of actions were identified: those that are externally paced and require dynamic interception of moving objects and as such involve *extrinsic guidance*; and those that are internally paced involving interaction with stationary objects that require *intrinsic guidance*. Since the formulation of general tau theory, research has predominantly focused on the study of intrinsic guidance with support for τ-coupling found in tasks ranging from nutritive sucking in preterm infants (Craig & Lee, 1999) to balance control (Austad & van der Meer, 2007; Spencer & van der Meer, 2012) and the swing of putting in golf (Craig, Delay, Grealy, & Lee, 2000). In the current paper, in order to gain greater insight into this model, the nature of extrinsic τ-coupling during interceptive reaching actions under varying task constraints was examined.

General tau theory (Lee, 1998) proposes that the central task in guiding any movement is controlling the closure of spatial and/or force gaps between effectors and their goals. According to the theory, guiding movement requires perception of the closure of gaps in perceptually available input arrays. What is perceived and controlled constantly to guide the movement is *tau* (τ), the time-to-closure of each spatial and/or force gap at its current closure rate. The main tenet of the theory is that the principal method of movement guidance is the coupling of the τs of different motion gaps, that is, their time-to-closure at current closure rate are held in a constant ratio *k*, as in: $\tau_Y = k\tau_X$. Lee (1998) argued that the parameter *k,* in this coupling equation relates to the velocity profile of τ-coupled movements.

That is, Lee mathematically showed that as k increases the duration of the acceleration phase of a goal directed movement increases, the peak velocity occurs progressively later in the movement and the braking/deceleration of the movement becomes more abrupt. Thus, with low values of k ($0 < k < 0.4$) the closure of the gap between effector and goal is soft and the velocity of gap Y relative to gap X reaches zero at impact, whereas at high k values ($0.4 < k$) the closure is hard with the gap closure velocity being positive prior to contact. Therefore, the higher the value of k, the higher the velocity at contact. As a result, it was proposed that parameter k reflects the regulation of the kinematics of closure of the gap and can serve as a descriptor of the terminal kinematics of the action.

Empirically establishing the presence of τ-coupling, and subsequently expressing the ratio of τ-coupling by parameter k, is typically achieved using a recursive linear regression analysis of the τs of two motion gaps (Lee, Craig, & Grealy, 1999; Lee, Georgopoulos, Clark, Craig, & Port, 2001). This process involves regressing two τs onto one another and applying a linear regression algorithm iteratively, initially including all of the data points and on each repetition of the regression discarding the first data point from the start of the movement. This process is repeated until the r^2 of the regression reaches 0.95 or greater (a criterion value set by the experimenters), whereby the algorithm takes that point to be the start of the linear relationship. The extent of τ-coupling is then expressed in terms of two variables: 1) the duration of coupling as a percentage of movement time; and 2) the value of parameter k indicated by the slope of the regression line.

Empirical values of k (as expressed in Lee, 1998) have been reported in a number of studies. Craig and Lee (1999) examined the intraoral sucking pressure of new-born infants. They found evidence of τ-coupling in both the increasing and decreasing suction periods of the infants' suck. The mean k values were significantly higher in the increasing suction period indicative of a forceful approach to the peak negative pressure (mean *k* =0.68), compared to a more gentle approach during the decreasing suction period (mean *k* =0.2). This finding was interpreted in relation to the different goals associated with the two phases of the suck. Austad and van der Meer (2007), also utilised *k* values to examine development of dynamic balance control during gait initiation, in children and adults. Using center of pressure data from force plate measurements, they found that mean *k* values decreased significantly with age and were for 2-3 year-olds 0.56, for 4-5 year-olds 0.50, for 7-8 year-olds 0.47, and for adults 0.41. They concluded that the control of dynamic balance develops from the youngest children colliding with the boundaries of the base of support to the older children and adults making touch contact (see also Spencer & van der Meer 2012 for a similar analysis of *k* in dynamic balance across adulthood).

In terms of extrinsic τ-coupling only a few published studies currently exist. Lee and colleagues reported a computer based interception task (Lee, et al., 2001) in which participants were required to move an on-screen cursor using a mouse in order to intercept a moving target as it arrived at a goal area. Results indicated that participants achieved the task by keeping τ of the gap between the cursor and target coupled to τ of the gap between the cursor and the destination zone, indicative of moving so as to keep the τs coupled in constant ratio. In this study no empirical *k* values were reported. It should be noted that the requirements of this task, as in many computer based experiments, were performed under high spatial and temporal constraint, that is, needing high spatial and temporal precision, minimising the variability in movement trajectories. Kayed and van der Meer (2009) investigated the development of prospective control of catching of full-term and preterm infants. They found that that there was little difference between full-term and preterm infants' use of timing strategies. Initially, infants used a distance- or velocity-strategy, both of which were related to many unsuccessful catches. After a shift to a time-strategy, infants appeared to increase the number of successful catches and performed longer and more functional τ-couplings between the hand and the toy. The study reports *k* values ranging from 1.18 to 0.85. Both preterm and full-term infants performed collisions with lower *k* values at 48 weeks compared to at 40 weeks. Further, the infants using a time-strategy had lower *k* values than the infants switching from a distance or velocity strategy to a time strategy. These findings indicated that as babies became older and developed more effective time-based strategies they made less forceful hand object contact when catching.

According to the model of τ-coupling described in Lee (1998) and Lee et al. (1999) the kinematics of the reaching movement can be regulated by setting the constant *k* at an appropriate value. As the value of *k* determines the kinematics of gap closure, different forms of velocity profiles are determined by the *k* values (Craig & Lee, 1999). This suggests that the value of the coupling constant *k* reflects how an actor *intends* to approach an object. As such it is predicted that the value of *k* reflects the degree of spatial and temporal constraint of the reaching action. However, the concept of *k* as a descriptor is based on the hypothesis that it remains at a constant value from the outset of the movement (or the onset of coupling, (Craig & Lee, 1999; Lee, et al., 1999; Lee, et al., 2001). This important assumption associated with τ-coupling will be referred to here as *the constant k hypothesis*.

Although in the literature many agree that τ has been successful in helping to understand various movements such as braking and interception, also various criticisms have been formulated against general tau theory and its role in the guidance of on-going movement. For instance, Land (2009) argued that though many movements might be consistent with the formulations as described by the theory, in that the dynamics fit the equations, any mechanism that works could fit such a formulation (see also Brouwer, Brenner, & Smeets, 2003, Tresilian 1997, 1999). Further, Land argued, general tau theory implies a mechanism linked exclusively to the monitoring of time-to-closure, whilst many other accounts of movement control have been developed that do not require continuous monitoring of environmental information. Finally, general tau-theory does not identify the control variables actually used, and how they are used, hence, Land and others have argued that the extent that general tau theory has explanatory power in other contexts is debatable. A large part of the criticism voiced is concerned with the nature of perception in motor control and the guidance of continuous movement. That is, whether the role of perception in action is unmediated by cognition and direct of environmental variables such as τ, or rather, that control is achieved by internally generated ‘forward models’ (cf. Wolpert & Flanagan, 2001) and other principles of indirect perception (for a review see Cisek and Calaska, 2010).

We recognise that perception for action is not only dealt with by ‘simple’ global invariants at the sensory level as proposed by Lee (Bradley & Goyal, 2008). For instance, Regan (2002) and others have shown that timing estimates can be made by using binocular information only, emphasising the role of stereovision, and its contribution to perception of interceptive actions (see also Gray & Regan, 1998). The nature and role of direct/indirect perception in action continues to be a matter of debate. In the current paper though, we are not concerned with this but rather, we are focusing on an evaluation of extrinsic τ-coupling patterns in a task that requires online movement tracking. In doing so we aim at further development and application of this aspect of the general tau theory.

As we have seen, Lee’s (1998) original model of extrinsic τ-coupling offers hypotheses regarding the relationship between parameter *k* and the kinematics of an action. The τ-coupling model predicts that *k* provides information about both the kinematics of gap closure (a continuous measure, evidenced in the velocity profile) and a descriptor of terminal kinematics of action (an endpoint measure reflected in the contact made with the object). According to this model, if an individual were to reach to lift an object off a moving target, under low spatial or temporal constraints (for instance moving at their own pace), they would produce movements with a different *k* value than when the task required the same object to be picked up as quickly as possible (under high temporal constraint).

To date, a systematic analysis of the τ-coupling constant *k* throughout movements with different kinematic constraints has not been performed. The literature so far has mainly looked at *k* as represented by the average slope in the regression analysis and assumed that it is constant. In the current paper we are looking to see if this is the case and how it might change with different conditions. By analysing the relationship between *τ*s over time (see Equation 1), it will be possible to determine if the ratio, here referred to as Kappa and denoted by K(t), remains stable and consistent during the course of *τ*-coupling of interceptive reaching towards a moving target, or whether it varies throughout the unfolding of the action (cf. Schögler, Pepping, & Lee, 2008). A clearer link can then be made between the variable *k* and the observed kinematics of interceptive reaching movements.

$$K(t) = \tau_Y(t) / \tau_X(t) \qquad (1)$$

The principle research question addressed was: How is the variability of this continuous counterpart of the coupling constant *k*, K(t), linked to the regulation of kinematics in interceptive reaching under varying task constraints? To address this, the spatial and temporal constraints of a reaching action were manipulated in order to alter both the velocity profile and end kinematics of the interception (Gentilucci, Toni, Daprati, & Gangitano, 1997; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990). Firstly, with regard to the variable *k*, and in line with the constant *k* hypothesis, it was predicted that movements with different kinematics should result in different *k* values. Next, we predicted that kinematics would manifest themselves in the continuous K(t) plots. To this end, *variability* of K(t) was examined throughout the reach to provide a continuous examination of the τ-coupling ratio. Finally, we wanted to see how, or if, K(t) changes under varying task constraints.

We applied general tau theory to investigate the extrinsic τ-coupling of the closure of gaps between the effector (hand) and a moving target object and between the hand and the interception place. The gaps selected for analysis were based on Jeannerod's (1984) description of reaching, where the hand transport component of successful interception can be viewed as the process of ensuring that the gap between the hand and the object is closed in a controlled manner (cf. Lee et al., (2001).

Method

Design

Participants were asked to remove a small object from a toy train moving at a constant velocity round an oblong shaped track (see Figure 1). Task constraints were manipulated using three conditions with increasing levels of spatial and temporal constraint. In the first, the object was to be picked up anywhere on the straight section of the track, resulting in both the spatial and temporal requirements being left *unrestricted, or open*. In the second, the object was to be picked up as accurately as possible at a specified point on the straight section of the track but participants were free to start their reach at any time, resulting in the requirements being *spatially specified* and the temporal requirements left unrestricted. In the third condition, the object was to be picked up as quickly and as accurately as possible at a specified point on the straight section of the track, that is, the participants were told to wait as long as possible before initiating the reaching movement. Hence, in the third condition the requirements of the task were *spatially and temporally specified*. Accordingly, the first condition is referred to as the open condition, the second as the spatial condition and the third condition the spatial-and-temporal condition.

Participants

Seven right-handed participants with normal or corrected-to-normal vision volunteered to take part in the experiment. Participants consisted of three females and four males (mean age = 27.7 years). The study was conducted in accordance with local ethics committee guidelines of the University of Edinburgh. All participants gave informed consent prior to participation and were free to withdraw from the experiment at any time.

Equipment and data recording

The experimental set-up consisted of an oblong track that measured 121.5 cm by 58 cm, with a total track length of approximately 288 cm, see Figure 1. The straight sections of the track were 64 cm long. Participants were required to kneel in front of the track. Exactly how this was achieved was left relatively unrestricted, provided they were in front of the straight section of the track and were able to begin the movement with their hand placed on the start position. The hand start position marker (30 mm by 30 mm square) was located to the right of the participant, and was positioned perpendicular to the edge of the track and 20 cm in front of it. A battery operated train moved in a clockwise direction around the track (at a speed of 226 mm/s) ensuring that the train approached from the participant’s right side. The object positioned on top of the train was a toy driver (measuring 65 mm high, 40 mm wide and 15 mm deep). The size of the surface area that the driver was positioned on was 125 mm long and 60 mm wide. Additionally, in the spatial and spatial-and-temporal conditions, a target marker (30 mm by 30 mm square) indicating the point at which the toy should be removed from the train was placed in line with the end of the straight section of the track (on the left side of the participant).

Movements were recorded in three dimensions, at a sampling frequency of 240 Hz, by a three-camera Qualisys movement registration system. Two 5 mm spherical light reflective markers (recorded to an accuracy of approximately 0.3 mm) were used, one attached to the top of the object, the other positioned on the posterior surface of the participants right hand, on the base of the first and second metacarpals. Cameras were mounted on fixed supports above the calibrated workspace.

Figure 1 here

Procedure

Before every trial, participants were asked to place their right hand on the start position. The directions given to each participant were to pick the ‘train driver’ up off the moving train, in accordance with the instructions that had been given for that particular condition, and to place the toy back on the starting position marker. In the open condition participants were instructed to pick the ‘train driver’ up off the moving train anywhere on the 64 cm straight section of the track (resulting in a distance to be reached of anything between 20 cm and 67 cm). In the spatial condition, participants were instructed to pick the ‘train driver’ up off the moving train as accurately as possible when the train was in line with the target marker positioned at the end of the track. In the spatial-and-temporal condition, participants were instructed to pick the ‘train driver’ up off the moving train as quickly as possible whilst still ensuring that the train was in line with the target marker positioned at the end of the track, that is, the participant should wait as long as possible before initiating the reaching movement.

The experiment consisted of 30 trials, ten for each of the three task conditions. Two practice trials of each condition were given to familiarise the participants with the task. The task constraint conditions were presented in a blocked sequence, with the open condition trials being first, followed by the spatially specified condition trials and the spatially-and-temporally specified condition presented last.

Data screening and analysis

Data smoothed using a Gaussian filter (sigma level 4), were analysed in a program developed using LabVIEW 7.1 software (National Instruments). Hand peak velocity (mm/s), derived from the movement of the hand marker, was used to determine the start and end of the movement: the start of the reaching movement was defined as the first point at which the velocity of the hand exceeded five percent of the hand peak velocity; the end of the movement was identified as the latest point at which the velocity of the closure of the gap between the hand and the object was above five percent of the peak velocity of the gap between the hand and the object. Trials in which the hand or object markers were occluded prior to object contact were not included within the analysis. This resulted in an average of nine trials per participant in the open condition, seven trials for each participant in the spatial condition and all but one participant had eight trials for the spatial-and-temporal condition. One participant had no complete trials for the spatial-and-temporal condition and was removed from the analysis for that condition, but was included in the open and spatial condition comparisons across movement kinematics, recursive linear regression and kappa.

The first stage of the analysis focused on examining the movement kinematics, in order to determine the effect manipulation of the independent variable, task instruction, had on the reaching actions. Repeated measures ANOVA with main effect of task condition (x3) were performed on movement time and peak hand velocity (using simple contrasts). To examine the temporal phasing of the movement, four critical movement phases were identified, which map onto those commonly examined in the reaching literature (Churchill, Hopkins, Ronnqvist, & Vogt, 2000; Gentilucci, et al., 1997; Smyth, Anderson, & Churchill, 2001): Phase 1, from the start of the movement to the moment of peak acceleration; Phase 2, from peak acceleration to the occurrence of peak velocity; Phase 3, from peak velocity to the moment of peak deceleration, and finally Phase 4 was determined from peak deceleration to the end of the movement. The hand velocity and acceleration profiles were calculated from the displacement of the hand marker. The absolute duration of each phase and their duration as a percentage of total movement time were calculated for each trial. The temporal contribution of each movement phase was analysed using a two-way ANOVA with repeated measures for condition (x3) and phase (x4). In order to provide a measure of the bell-shaped distribution of the velocity profile, planned contrasts examining the symmetry of the phases compared Phase 4 to Phase 1 and Phase 3 to Phase 2.

Analysis of τ-coupling measures. τs were calculated for the gap between the hand and the object (HO), and the gap between the hand and the point of interception (HI) as can be seen in Figure 1. Additionally, Figure 2 shows the detailed progression of the τ-coupling analysis for individual trials from two participants. The sizes of the gaps, r, and the rate of change of the gap closure, $\dot{r}$, were calculated as a time series using the displacement between the two ends of the gap at any moment in time (Figure 2A and B). The τ of the gaps at each time sample t, was then calculated by dividing r, at each time t, by $\dot{r}$ at that time, using Equation 2 (Figure 2C and D).

$$\tau_r = r / \dot{r} \tag{2}$$

Figure 2 here

The τ-coupling examined in the present study was $\tau_{HO} = k\ \tau_{HI},$ where gap *Y* was *HO* (hand-object) and gap *X* was *HI* (hand-interception). The linear relationship during the movement between the two τs (τ_{HO} and τ_{HI}) was derived using a linear regression algorithm. This involved regressing τ_{HO} against τ_{HI} (see Figure 2E and F). To calculate *k*, a sequence of calculations was performed (recursive liner regression analysis) to find the beginning of the linear relationship between consecutive data points that ended at the moment of object contact. This was done using a linear regression algorithm applied iteratively, initially including all of the data points and on each repetition of the regression the first data point from start of the movement was discarded. This process was repeated until the r^2 of the regression reached 0.95 or greater, whereupon the algorithm took that point to be the start of the linear relationship. The variables analysed from the recursive linear regression were the relative duration of the linear τ-coupling relationship expressed as a percentage of movement time, and *k* obtained from the slope of the linear regression equation (see Figure 2E and F).

The outcome variables of relative duration of coupling and *k* were statistically analysed using repeated measures ANOVA with 3 levels of condition.

To allow a continuous inspection of the τ-coupling ratio during the entire movement K(t) was examined throughout the reach. K(*t*) from Equation 1, was calculated at each time sample, *t*, where gap *Y* was *HO* and gap *X* was *HI* resulting in (see Figure 2G and H):

$$\mathrm{K}(t) = \tau_{HO}(t)/\tau_{HI}(t) \tag{3}$$

To enable a comparison between the kinematic changes and the variability of K(t) within a trial, the data for each interception were divided into four different movement phases: representing the initial acceleration, high velocity acceleration, high velocity deceleration and final low-velocity phase of the reaching movement (see also phase duration as a percentage of movement time). The within trial duration, mean (M), standard deviation (SD) and coefficient of variation (CV) of K(t) were then calculated for each movement phase. The within trial SD of K(t) was taken as a dependent variable representing the variability of K(t) within each of the four movement phases (hereafter referred to as VarK, see Figure 5 and Table 2). To test whether K(t) was held constant throughout each of the 4 phases of the reaching movement a two-way ANOVA with repeated measures for condition (x3) and phase (x4) was performed on the VarK (and adjusted using Huynh-Feldt correction).

Mean K(t) within a phase (MeanK), on the other hand, provided a measure of the absolute ratio of coupling during each movement phase. To determine whether K(t) was sensitive to task constraints, the effect of condition on MeanK was tested for Phases 2, 3 and 4 – Phase 1 could not be included in this analysis as the large variability observed in K(t) violated the assumption of equal variance. A two-way ANOVA was performed on MeanK, with repeated measures for condition (x3) and phase (x3).

Results

Movement kinematics

These initial analyses aimed to address whether the instructional manipulation of spatial-temporal task constraints were indeed effective. There was a significant main effect of task condition on movement time (*F*(2, 10) = 19.79, $p < 0.01$, partial $\eta^2 = .80$). Movement times observed in the spatial-and-temporal condition were significantly shorter than those observed in both the open condition (*F*(1, 5) = 49.75, $p < 0.01$, partial $\eta^2 = .91$) and the spatial condition (*F*(1, 5) = 39.62, $p < 0.01$, partial $\eta^2 = .89$). That is, mean movement times in the spatial-and-temporal condition (*M* = 452, *SD* = 56 ms) were almost half that taken in the open condition (*M* = 750, *SD* = 21 ms) and the spatial condition (*M* = 884, *SD* = 202 ms). There was also a significant main effect of task condition on peak hand velocity (*F*(2, 10) = 115.53, $p < 0.01$, partial $\eta^2 = .96$). Hand peak velocity in the open condition was significantly lower than the spatial condition (*F*(1, 5) = 13.91, $p < 0.05$, partial $\eta^2 = .74$) and the spatial-and-temporal condition (*F*(1, 5) = 124.54, $p < 0.01$, partial $\eta^2 = .96$). The spatial condition also exhibited hand peak velocities significantly lower than the spatial-and-temporal condition (*F*(1, 5) = 348.07, $p<0.01$, partial $\eta^2 = .99$). Taken together these effects substantiate the effectiveness of the instructional manipulation.

Figure 3A shows the temporal contribution of each movement phase as a percentage of movement time. No main effect of task condition on phase duration was found (*F*(2, 10) = 1.21, *ns*), but a main effect of phase was observed (*F*(3, 15) = 12.62, $p < 0.01$, partial $\eta^2 = .72$). Planned contrasts revealed that Phase 4 was significantly longer than Phase 1 (*F*(1, 5) = 22.03, $p<0.05$, partial $\eta^2 = .82$) and that Phase 3 was significantly longer than Phase 2 (*F*(1, 5) = 29.92, $p<0.05$, partial $\eta^2 = .86$). Therefore, the four phases were not equally distributed; the longer decelerative phases (Phases 3 and 4) indicate a non-symmetrical velocity profile, with a larger proportion of deceleration than acceleration (see Figure 3A). A significant condition x phase interaction was found (*F*(6, 30) = 6.25, $p < 0.01$, partial $\eta^2 = .56$). To break this down, contrasts were performed comparing the acceleration (Phases 1 vs 2) and deceleration (Phases 3 vs 4) for all three conditions. The contrasts revealed no effect of condition on the duration of Phase 1 compared to Phase 2, indicating there was no effect of condition on the duration of the accelerative phases. In terms of the deceleration, the contrasts showed that the duration of Phase 3 compared to Phase 4 in the spatial-and-temporal condition was significantly different to the other two conditions. The short duration of Phase 3 (compared to a longer Phase 4) did not differ between the open and the spatial conditions ($F(1, 5) <1$, *ns*). Meanwhile in the spatial-and-temporal condition, the long duration of Phase 3 (compared to a short Phase 4) was significantly different than in both the open condition ($F(1, 5) = 8.01$, $p < 0.05$, partial $\eta^2 = .62$) and in the spatial condition($F(1, 5) = 9.45$, $p < 0.05$, partial $\eta^2 = .65$) (see Figure 3A).

Figure 3 here

Recursive linear regression analysis

If the measures of extrinsic τ-coupling obtained from the recursive linear regression (i.e. duration of coupling and constant *k* value) reflect the observed velocity profiles and terminal kinematics of the reaching action, then we would expect to find an effect of task condition on both these variables. A summary of the τ-coupling regression variables for the task conditions can be found in Figure 3B and C. The mean (with standard deviations in parentheses) percentage of movement time of the hand transport that corresponded to the straight section of the τ_{HO} versus τ_{HI} recursive linear regression graphs was: 98.5 % (1.9 %) for the open condition, 91.3 % (6.6 %) for the spatial condition and 91.0 % (15.2 %) for the spatial-and-temporal condition. No main effect of task condition was found on the duration of the linear relationship between the selected τs as a percentage of the total movement time ($F(2, 10) = 1.16$, *ns*). The mean value of *k* over participants was 0.97 (*SD* = 0.34) for the open condition, 1.31 (*SD* = 0.04) for the spatial condition and 1.29 (*SD* = 0.16) for the spatial-and-temporal condition. Similarly, no main effect of task condition was found on the constant *k* value (*F*(2, 10) = 3.6, *ns*). These findings indicate that the kinematic differences observed as a result of manipulating task conditions were not reflected in the measures obtained from the recursive linear regression analysis. That is, by employing solely the recursive linear regression it was not possible to distinguish between the three experimental conditions.

Kappa analysis

Figure 4 shows the continuous ratios K(t) for each individual participant. If linearity is to be assumed from the beginning of the movement, or even from the beginning of the coupling, then K(t) should remain stable until the end of the movement. Therefore, the question of interest here is whether the variance in K (VarK) was held small and the value of K (MeanK) was held constant throughout each of the 4 phases of the reaching movement.

Table 1 here

Table 1 shows the individual participant values of MeanK, VarK as well as the coefficient of variation (CV) of K(*t*) for each phase of the movement. In the first phase participants 1-3 had a strategy of maintaining a low variation in K(*t*) for the open condition but varied K(*t*) considerably during the spatial and spatial-and-temporal condition. Participants 4-6 on the other hand showed considerable variation in K(*t*) in the first movement phase in all conditions. In the second and third phases all participants had minimal variation in their strategies with MeanK values ranging from .83 – 1.19. In the final movement phase all of the participants showed more variation in their action strategies compared to phases 2 and 3, but less variation compared to phase 1. The range of MeanK values in the last phase of the movement was lower than in the other phases, ranging from .2 – .9. These results are also reflected in Figure 4.

Figure 4 here

An analysis of the VarK showed there was a significant main effect of condition ($F(2, 10) = 4.15, p<0.05$, partial $\eta^2 = .45$). Contrasts revealed that the open condition had a significantly lower VarK than the spatial condition ($F(1, 5) = 6.65, p<0.05$, partial $\eta^2 = .57$). That is K(t) was more stable in the open condition than in the spatial condition. A significant main effect of phase ($F(1.00, 5.02) = 50.61, p < 0.01$, partial $\eta^2 = .91$, adjusted using Huynh-Feldt) was found. The contrasts revealed that VarK in Phase 1 was significantly higher than Phase 2 ($F(1, 5) = 51.91, p < 0.01$, partial $\eta^2 = .91$), VarK in Phases 2 and 3 did not differ ($F(1, 5) < 1$, *ns*), and finally VarK in Phase 4 was significantly higher than in Phase 3 ($F(1, 5) = 172.81, p < 0.01$, partial $\eta^2 = .97$). That is, K(t) was highly variable in Phase 1, remained stable with low variability in Phases 2, 3 and became slightly more variable again in Phase 4. Moreover, a significant condition x phase interaction ($F(2.93, 14.66) = 4.20, p<0.05$, partial $\eta^2 = .46$) revealed that VarK in Phase 1 was significantly lower in the open condition compared to the spatial condition ($F(1, 5) = 6.61, p=0.05$, partial $\eta^2 = .57$); indicating that K(t) in Phase 1 of the open condition was less variable than in Phase 1 of the spatial condition (see Figure 5). Together these findings indicate K(t) is held relatively constant through some but not all phases of the action.

To examine the effect of condition on K(t), MeanK for Phases 2, 3 and 4 were analysed – Phase 1 was excluded from this analysis as the large variability observed in the SD of K(t) violated the assumptions of equal variance. In terms of MeanK, there was a significant main effect of condition ($F(2, 10)$ 6.40, $p = 0.05$, partial $\eta^2 = .56$). Contrasts revealed that the spatial-and-temporal condition had a significantly lower MeanK than the open ($F(1, 5) = 9.64, p<0.05$, partial $\eta^2 = .66$) and spatial ($F(1, 5) = 7.46, p<0.05$, partial $\eta^2 = .60$) conditions. A significant main effect of phase ($F(2, 10) = 27.27, p < 0.01$, partial $\eta^2 = .85$) revealed that while there was no significant difference in MeanK between Phase 2 and

Phase 3 (*F*(1, 5) < 1, *ns*), MeanK in Phase 4 was significantly lower than in Phase 3 (*F*(1, 5) = 28.54, *p*<0.01, partial η^2 = .85) and Phase 2 (*F*(1, 5) = 61.63, *p*<0.01, partial η^2 = .93).

Finally a significant condition x phase interaction (*F*(1.99, 9.92) = 8.57, *p* < 0.01, partial η^2 = .63, adjusted using Huynh-Feldt) was found (presented in Figure 5B). To break this down, repeated contrasts were performed comparing Phases 2 and 3, and Phases 3 and 4 for all three conditions. The contrasts revealed no significant difference between the open and the spatial conditions in the MeanK of Phase 2 compared to Phase 3 (*F*(1, 5) 1.46, *ns*). However, there was a significant difference between the spatial condition and the spatial-and-temporal condition in the MeanK of Phase 2 compared to Phase 3 (*F*(1, 5) = 6.97, *p*<0.05, partial η^2 = .56). This indicated that the effect of condition was larger in Phase 3 than in Phase 2, namely in the spatial-and-temporal condition MeanK in Phase 3 became higher than in Phase 2, while in the spatial condition MeanK in Phase 3 became lower than in Phase 2. When examining the MeanK values of Phase 3 compared to Phase 4, there was a significant difference between the open condition and the spatial condition (*F*(1, 5) 6.51, *p*=.05, partial η^2 = .57) and the spatial condition and the spatial-and-temporal condition (*F*(1, 5) = 12.93, *p*<0.05, partial η^2 = .72), indicating that the effect of condition was larger in Phase 4 than in Phase 3. In the open condition MeanK in Phase 4 became slightly lower than in Phase 3. In the spatial condition MeanK in Phase 4 remained at the same value as in Phase 3. In the spatial-and-temporal condition MeanK in Phase 4 became considerably lower than in Phase 3. These findings indicate that the effects of task condition on MeanK can be observed in the interaction between Phases 3 and 4. This finding mirrors the effects observed in the movement kinematics on phase duration as a percentage of movement time. Specifically, in the spatial-and-temporal condition the long duration of Phase 3 (between peak velocity and peak deceleration) corresponds with a high MeanK; meanwhile the short duration of Phase 4 (between peak deceleration and the end of the movement) corresponds with a low MeanK.

Figure 5 and Table 1 here

Discussion

In the present study, the manipulation of task instructions was effective in producing three different reaching actions each with distinct velocity profiles and terminal kinematics. Mean movement times in the spatial-and-temporal condition were almost half that taken in the open condition and the spatial condition. This finding is in agreement with Wing, Turton and Fraser (1986), who found that ‘fast’ reaches were executed nearly twice as quickly as reaches for which no instructions were given. In relation to the temporal phasing of the reaching actions, the effect of task condition was evident in the proportion of Phase 3 to Phase 4. This is best explained in relation to the bell-shaped velocity profile utilised to describe the hand movement during reaching actions (Berthier, Clifton, Gullapalli, McCall, & Robin, 1996; Gentilucci, et al., 1997). Increased accuracy requirements, in this case the spatial condition, were associated with an asymmetric profile with an elongated deceleration, specifically a long tailing-off of the final low-velocity phase (Phase 4). This profile is reversed in the spatial-and-temporal condition with a ‘wider’ bell-shaped velocity profile to maintain high velocity of the hand for longer before a sudden and sharp deceleration, causing a short final low-velocity phase.

In terms of general τ theory (Lee, 1998), evidence for extrinsic τ-coupling was found for all participants in all three task conditions. The continuous guidance of hand transport could be explained by τ-coupling the closure of the hand-object gap with the hand-interception gap during the reaching movement. It was predicted that movements with different kinematics would result in different k values, but no evidence in support of this hypothesis was found. From the recursive linear regression analyses it was not possible to distinguish between the three experimental conditions. In describing how k is associated with the regulation of kinematics of action Lee (1998) proposed that as k increases, the duration of the acceleration phase increases, the peak velocity occurs later in the movement and braking becomes more abrupt. In the current experiment, although the movement time and hand peak velocity did differ between conditions, the duration of acceleration (Phases 1 and 2) as a percentage of movement time did not significantly differ between conditions. This may be due to the high accuracy demands already associated with intercepting a moving object. Instead results from the movement phase analysis indicated subtleties between task conditions in terms of the final hand deceleration towards the object, specifically the relative contribution of the high/low velocity deceleration phases (i.e. Phases 3 and 4). It appears that as a descriptor of movement kinematics k was not sensitive to such subtleties. These findings could suggest that in terms of the description of kinematics, the sensitivity of parameter k from the recursive linear regression is limited to the proportion of acceleration to deceleration within a task.

In principle, the constant k hypothesis implicitly assumes that K(t) is held constant throughout the movement. This was not found to be the case; instead K(t) was constant during some, but not all phases of the movement. The standard deviation of K(t), varK, was used to provide a measure of the stability of K(t). It exhibited high variability during the initiation phase and low variability, indicating high stability, during the remaining three phases, for all three task conditions. The high variability observed in K(t) during the initiation of the movement demonstrated that τ-coupling was not routinely established at the onset of the reaching movement. There are methodological and conceptual explanations for this finding. Firstly, a conceptual explanation for the absence of coupling during the initial acceleration is the possibility of a delayed onset of coupling during this first phase of the movement. That is, for τ-coupling to be established, information about the motion gaps has to picked up before they can be coupled (cf. Lee, et al., 1999). In this sense, it may be that the initiation of action will itself generate perceptual information essential for the regulation of τ-coupling.

The increased variability observed in K(t) at the beginning of the movement may also be due to the nature of the τ calculation, and its numerical solution from position and velocity data. Low velocity movements introduce inaccuracies to the calculated value of τ, due to the denominator, velocity of gap closure, exhibiting small values. This is also reported as the low velocity argument (see Bingham & Zaal, 2004). The reason the same variability was not found in the final low-velocity phase, which generally exhibited low variability over trials, is that the low velocity argument is amplified in the initial acceleration phase due to a larger nominator, namely gap size, in the τ calculation (see Equation 2).

In contrast to the results of the recursive linear regression, analysis of K(t) did reveal effects of task manipulations. The mean and standard deviation of K(t) can be described relative to the temporal structure of the movement, specifically the changing contribution of the deceleration phase of the interceptive reaching action. The relative duration and mean K(t) values of Phases 3 and 4 reflected the kinematics of the different task conditions: the spatial-and-temporal condition exhibited a higher mean K(t) in Phase 3 and lower mean K(t) in Phase 4 than the other two task conditions. In this instance, as opposed to a summary of the kinematics derived from *k*, a continuous description of the kinematics can be obtained from K(t). For example, throughout the middle section of the movement where the largest movement displacement was covered, a K(t) of around 1 indicated rapid acceleration, which if continued would result in collision with the object; however towards the end of the movement, in the final low-velocity phase, K(t) dropped to values below or around 0.5 indicating a controlled collision with the object.

Therefore, the analysis indicated that the pattern of the variability and mean K(t) exhibited in the initial acceleration and final low velocity phases were different from the stable patterns observed during the middle (distance covering high velocity acceleration and deceleration) phases of the movement. As such the phases may be seen as serving alternative goals. The final low-velocity phase towards the object is concerned with closing the fingers and thumb around the object to make controlled contact with it and lift it off a moving trajectory. It appears to be logical therefore that as the grasp becomes the dominant goal the end-effector would be expected to change from the wrist, to the thumb and fingers. It is possible therefore that in the final low-velocity phase another τ-coupling comes into effect, involving gaps that are most relevant in relation to the grasp.

These findings have broad implications for considerations of general τ theory in terms of methodology and conceptualisation. A main condition of the recursive linear regression is that the linear relationship must extend up until the point of contact, therefore, there is an implicit assumption that there is a linear τ-coupling relationship during the final low-velocity phase of the movement. The K(t) results indicated that this was not the case. The ratio of coupling of the hand-object gap to the hand-interception gap was not held constant until contact, as seen in the decrease of K(t) at the end of the movement. Therefore, the τ-couplings examined in the current study were not a constant linear relationship throughout the entire movement, but instead, evolved throughout the on-going movement. The stability of K(t) provides a continuous description of the ratio of closure of the gaps. In comparison, the *k* value derived from recursive linear regression analysis provides an estimate for the entire movement, and as such has to be seen as a *summary* of the coupling. This suggests that what constitutes τ-coupling can be conceptualised in more than one way: either as gaps in a linear ratio with a single constant value, although not necessarily throughout the entire movement, in which case recursive linear regression may not be the most appropriate method of analysis as it assumes coupling until contact, or as τs, of gaps in a continuously changing ratio, in which case smooth non-linear patterns that are reproducible over trials can also be evidence of τ-coupling, requiring the examination of K(t).

The findings presented in this study highlight the importance of clarifying what constitutes as *τ*-coupling. Whether the relationship between the *τ*s must be linear and continue until the point of contact, *can* be linear during particular phases of the movement, or can even be non-linear; and whether low-variability over trials and participants is indicative of the use of a τ-coupling strategy. Therefore, it is suggested here that in order to fully understand extrinsic τ-coupling in interceptive reaching, perhaps more complex couplings, such as those systematically varying the ratio between two τs over time, may now be necessary. This idea is echoed by the notion that information about the current future allows prospective control, that is, control ahead of time (Bootsma, Fayt, Zaal, & Laurent, 1997; Bootsma, 2009; Hofsten, 1993; Lee, 1993). Prospective control entails that things change during the course of a movement and that the future will be different. Collision can be avoided and careful interception achieved because of the availability of gap closure information about time to collision if the current speed of approach is maintained. Gap-coupling in that sense can be seen as a motor control strategy that uses information about the current future that establishes a required temporal relation that can be influenced so as to fulfil the action goal of attaining the desired future (Bootsma, 2009; Bootsma, et al., 1997). With these developments interpretation of what may constitute as gap-coupling may appear increasingly more complex. The data presented here, therefore, emphasises the importance of the logical selection of appropriate gaps and that K(t) profiles be treated with a rational reference to the complexities of the given task, its movement goals and the resultant observed kinematics.

The findings presented can be compared to those reported by other researchers. For instance, Hopkins and colleagues (Hopkins, Churchill, Vogt, & Ronnqvist, 2004) investigated whether the control of the decelerative phase of a reaching movement complies with a movement strategy that takes account of the rate of change of the diminishing visual gap between the hand and the object - also known as the tau-dot strategy in reaching (cf. Zaal & Bootsma, 1995). Also, Churchill et al. 2000 investigated reaching and found that removing environmental information during reaching to stationary objects had effects both early and late in the reach, while vision of the hand was only crucial in the zooming in period to contact after peak deceleration. These and other studies have investigated the role of tau or its time derivative tau-dot in braking movements (see also Bardy & Warren, 1997; Fajen, 2005). The analysis of K(t) presented here may also be a useful way to measure how the coupling of gaps evolves throughout these types of movement.

To conclude, an alternative τ-coupling analysis was introduced describing the continuous ratios of the τs of motion gaps relative to the kinematics of the phases of the reaching action. Combined with an appropriate scale, such as key movement phases, K(t) enables the examination of the evolution of gap couplings, which can indicate the role that perceptual information plays at critical moments during the movement. Using this method, future research could examine an account of movement guidance based on a nested set of τ-couplings, whereby the gap couplings used may change during the unfolding of the movement dependent upon evolving task goals. These findings offer an opportunity to expand on our present understanding of a coupling ratio and what it means to guide interceptive reaching movements by coupling the closure of gaps.

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Table and Figure Captions

Table 1. MeanK, VarK and coefficient of variation (CV) values of K(t)τ_{HO}–τ_{HI} coupling of all trials for each participant and condition in each of the four movement phases: 1 = start of the movement to peak acceleration; 2 = peak acceleration to peak velocity; 3 = peak velocity to peak deceleration; 4 = peak deceleration to movement end..

Figure 1. Diagram of the experimental set-up from above with a representation of the motion gaps involved in the experimental task. τ_{HO} is the τ of the hand-object gap, τ_{HI} the τ of the hand-interception gap and τ_{OI} the τ of the object-interception gap.

*Figure 2***.** Progression from gap measures to τ-coupling, for typical trials of two participants. A & B: the hand-object (HO) and hand-interception (HI) gap, and the corresponding rate of closure for each participant; C & D: τ_{HO} and τ_{HI} values plotted against time; E & F: results from the recursive linear regression of τ_{HO} and τ_{HI}; G & H: the $\mathrm{K}(t) = \tau_{HO}(t)/\tau_{HI}(t)$ plots for the data presented in Graphs E and F. The dashed horizontal lines in G & H indicate the *k* value obtained from the recursive linear regression. The dashed vertical line in H indicates the beginning of coupling obtained from the recursive linear regression.

Figure 3. A) Mean relative duration of movement phases as a percentage of total movement time. B) Mean duration of τ-coupling as a percentage of movement time, calculated using the recursive linear regression. C) Mean *k* value of τ-coupling, calculated using the recursive linear regression. The error bars represent one standrad deviation.

Figure 4. Time normalised profiles of $K(t)\tau_{HO}$–τ_{HI} coupling of all trials for each participant and condition.

Figure 5. A) VarK, B) MeanK, and C) a table with values of VarK and MeanK for each of the four movement phases in all three conditions.

Figure 1.

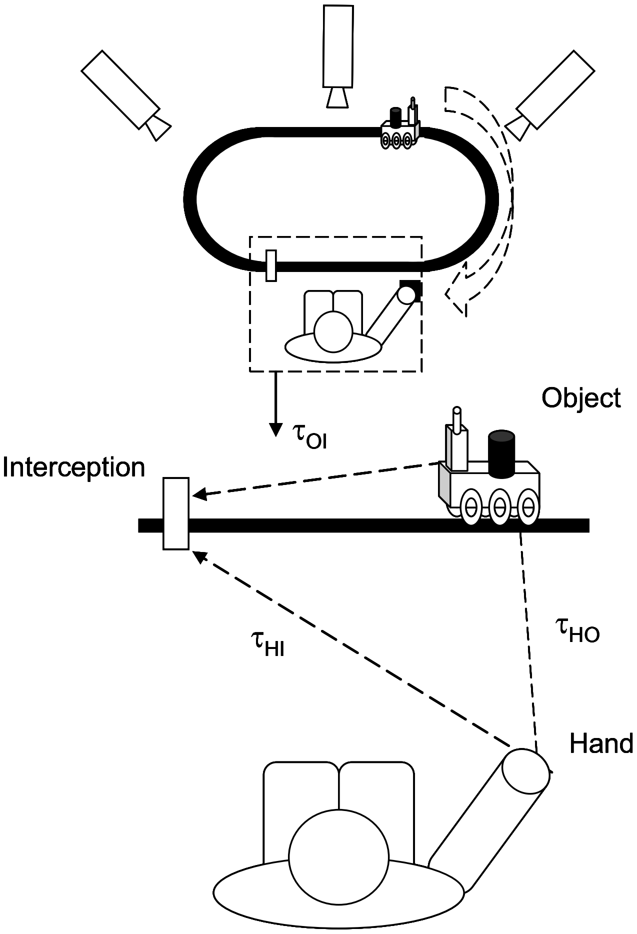


Figure 2.

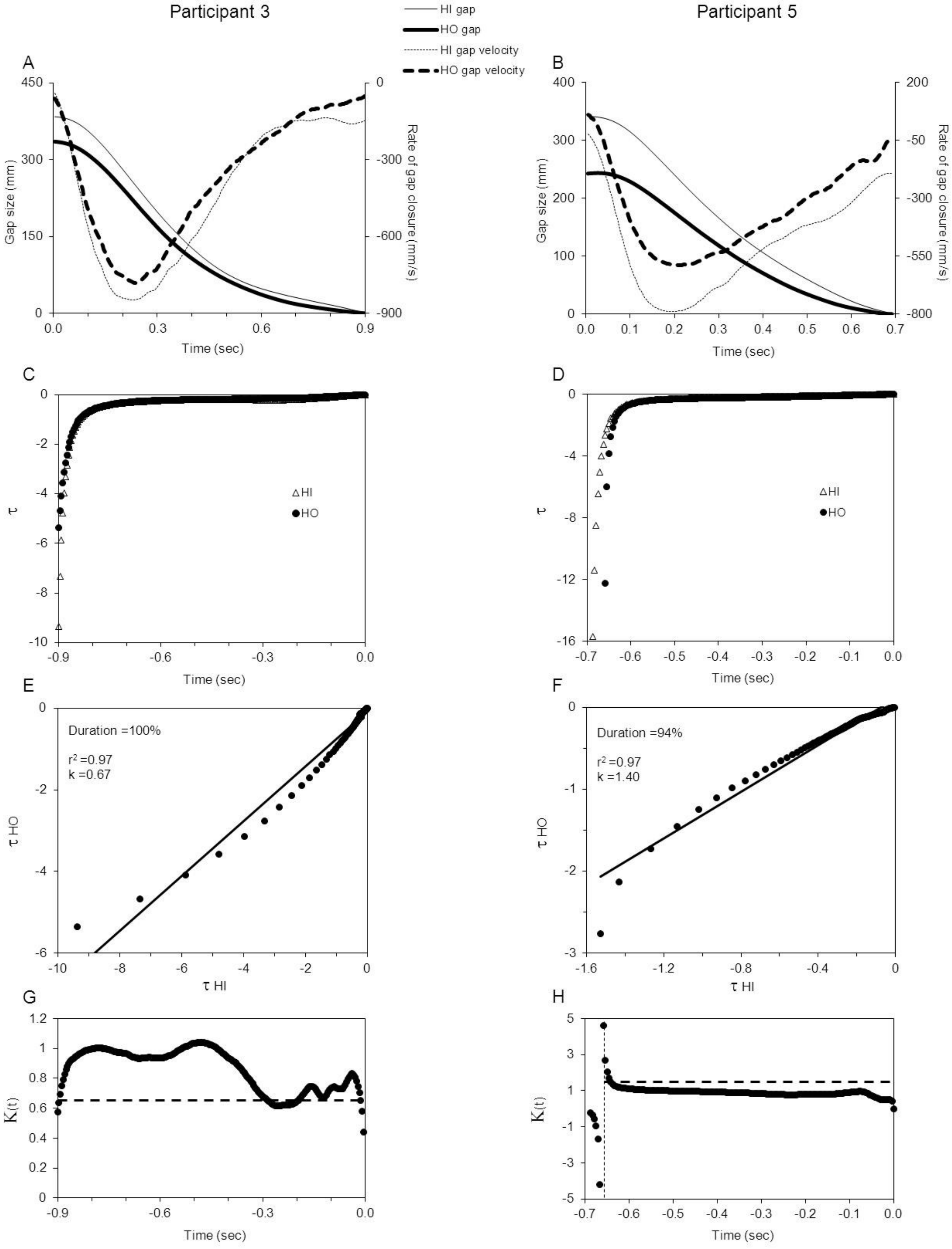

Participant 3
Participant 5
HI gap
HO gap
HI gap velocity
HO gap velocity
A
B
C
D
E
F
G
H
Gap size (mm)
Rate of gap closure (mm/s)
Time (sec)
τ
ΔHI
●HO
τ HO
τ HI
Duration =100%
r² =0.97
k =0.67
Duration =94%
r² =0.97
k =1.40
K(t)
450
300
150
0
-300
-600
-900
400
200
100
-50
-550
-800
0.0
0.3
0.6
0.9
0.1
0.2
0.4
0.5
0.7
-2
-4
-6
-8
-10
-12
-16
-0.9
-0.3
-0.7
-0.5
-0.1
-1
-3
-1.6
-1.2
-0.8
-0.4
1.2
1
0.8
0.6
0.4
0.2
5
3

Figure 3.

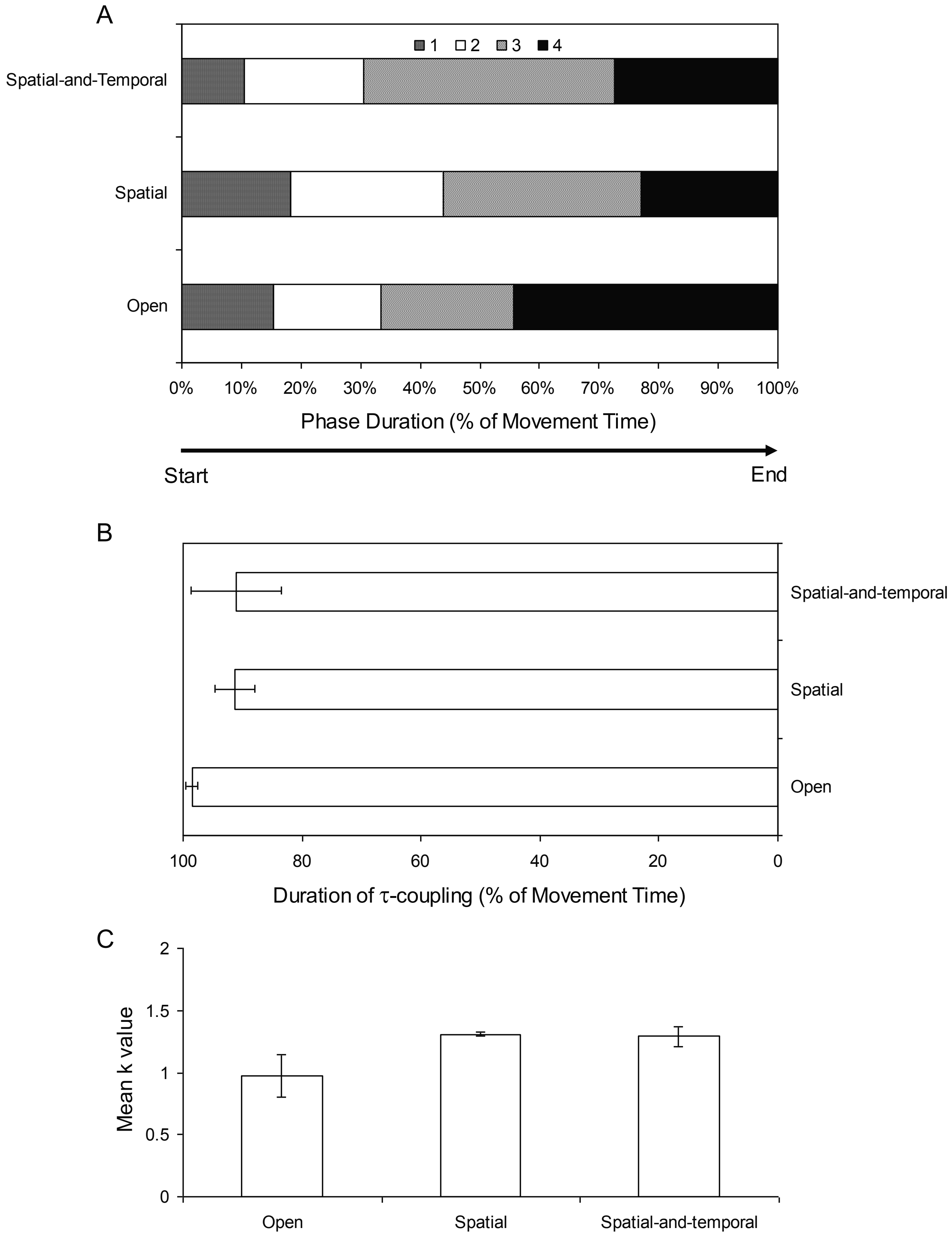

A
1
2
3
4
Spatial-and-Temporal
Spatial
Open
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Phase Duration (% of Movement Time)
Start
End
B
Spatial-and-temporal
Spatial
Open
100
80
60
40
20
0
Duration of τ-coupling (% of Movement Time)
C
2
1.5
1
0.5
0
Mean k value
Open
Spatial
Spatial-and-temporal

Figure 4.

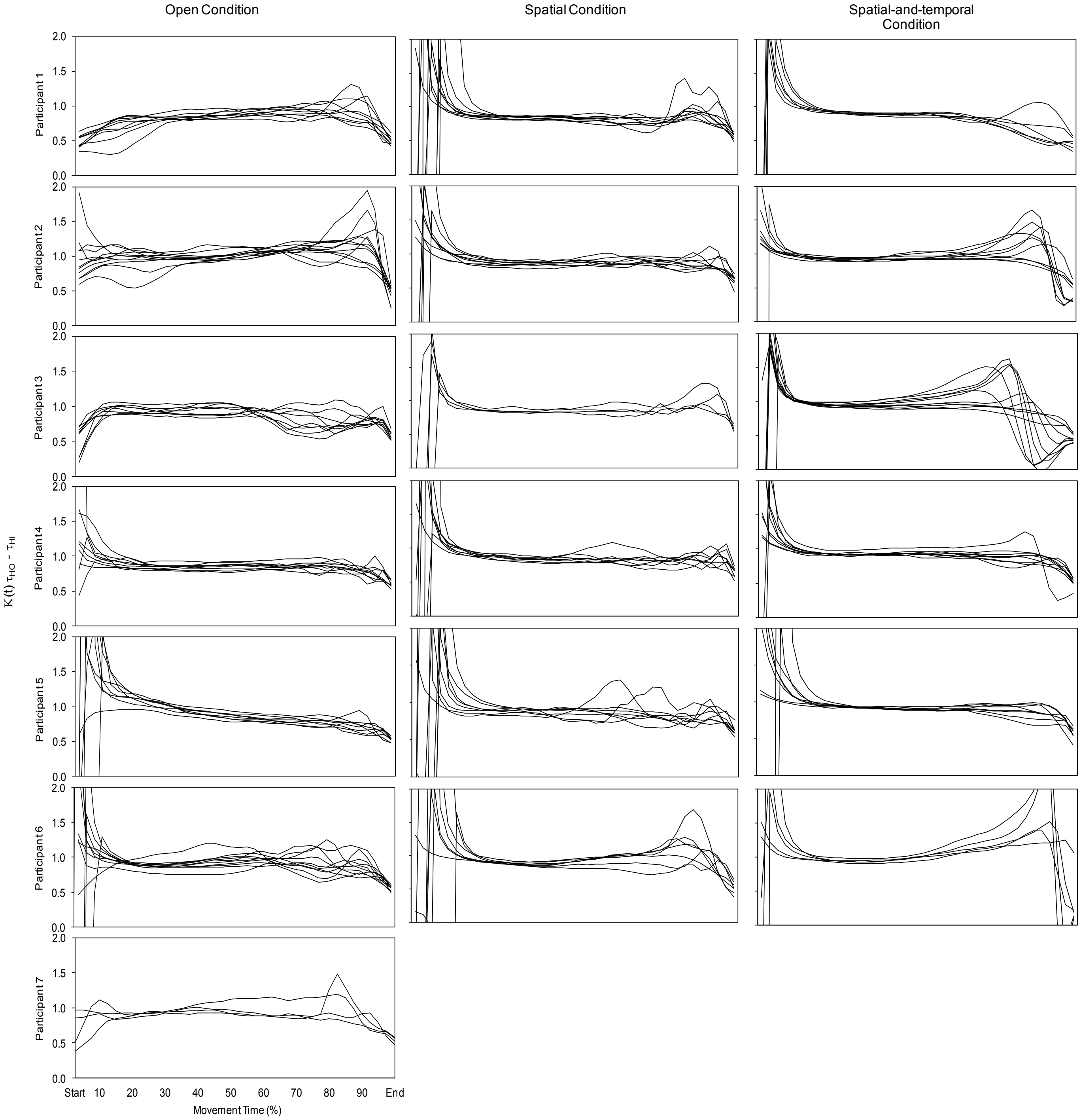
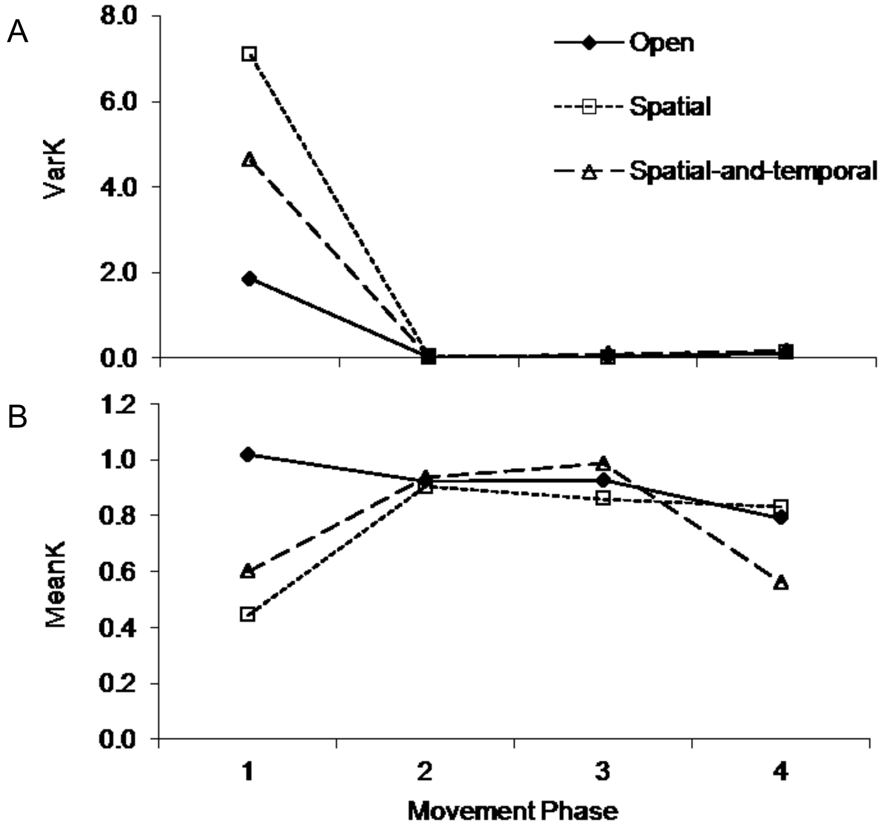

Open Condition
Spatial Condition
Spatial-and-temporal Condition
Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
K(t) τHO - τHI
2.0
1.5
1.0
0.5
0.0
Start
10
20
30
40
50
60
70
80
90
End
Movement Time (%)

Table 1.

		Task Conditions and Movement Phases											
	PP	Open				Spatial				Spatial and Temporal			
		Phase 1	Phase 2	Phase 3	Phase 4	Phase 1	Phase 2	Phase 3	Phase 4	Phase 1	Phase 2	Phase 3	Phase 4
MeanK	1	0.63	0.83	0.89	0.82	-1.50	0.87	0.83	0.78	0.33	0.92	0.89	0.73
	2	0.95	0.97	1.09	0.73	0.33	0.89	0.87	0.79	-0.48	0.93	1.00	0.56
	3	0.72	0.94	0.94	0.82	0.34	0.91	0.84	0.89	1.12	0.96	1.03	0.50
	4	1.23	0.86	0.85	0.80	1.42	0.91	0.84	0.82	1.30	0.94	0.92	0.62
	5	2.02	1.05	0.85	0.68	1.16	0.94	0.86	0.82	0.84	0.94	0.89	0.63
	6	0.55	0.89	0.94	0.88	0.92	0.91	0.91	0.89	0.50	0.95	1.19	0.32
	7	0.83	0.92	0.99	0.89	9.13	0.89	0.87	0.90				
VarK	1	0.11	0.02	0.03	0.14	14.39	0.04	0.02	0.12	6.91	0.02	0.01	0.15
	2	0.09	0.02	0.07	0.20	4.89	0.03	0.02	0.10	7.45	0.02	0.11	0.18
	3	0.15	0.02	0.02	0.12	3.73	0.07	0.01	0.11	4.45	0.02	0.10	0.18
	4	1.12	0.02	0.02	0.09	8.01	0.07	0.02	0.09	1.47	0.02	0.04	0.12
	5	6.25	0.11	0.03	0.09	6.84	0.08	0.03	0.11	2.85	0.02	0.04	0.13
	6	3.42	0.02	0.02	0.15	4.74	0.04	0.04	0.19	4.66	0.01	0.25	0.29
	7	0.10	0.03	0.02	0.16	43.09	0.02	0.01	0.11				
CV	1	0.18	0.02	0.03	0.17	-1.24	0.05	0.02	0.15	8.72	0.02	0.01	0.20
	2	0.09	0.02	0.07	0.30	7.38	0.04	0.03	0.13	-0.43	0.02	0.10	0.37
	3	0.23	0.02	0.02	0.14	7.31	0.07	0.02	0.12	5.91	0.02	0.09	0.46
	4	0.53	0.03	0.02	0.11	-29.96	0.07	0.02	0.11	1.44	0.02	0.04	0.21
	5	2.12	0.10	0.04	0.13	-3.88	0.08	0.04	0.13	-0.01	0.02	0.05	0.20
	6	-3.91	0.02	0.03	0.17	1.63	0.04	0.04	0.22	-0.36	0.01	0.20	-15.08
	7	0.14	0.03	0.02	0.18	7.45	0.02	0.01	0.12				

Figure 5



	VarK				MeanK			
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 1	Phase 2	Phase 3	Phase 4
Open	1.86	0.04	0.03	0.13	1.02	0.92	0.93	0.79
Spatial	7.1	0.05	0.02	0.12	0.4	0.90	0.86	0.83
Spatial-and-Temporal	4.6	0.02	0.09	0.17	0.6	0.94	0.99	0.56